Indirect method application for RI-beam experiments

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Hyper ECR ion source: Y. Ohshiro

in Collaboration with:

RIKEN, KEK, Kyushu, Tsukuba, Tohoku, Osaka (Japan),
McMaster (Canada), CIAE, IMP, Beihang (China), Chung-Ang, IBS, Ehwa, SKKU (Korea), INFN Padova/Catania (Italy), IOP(Vietnam) and others.

Topics

- Brief introduction of our RI beam separator CRIB (CNS, U-Tokyo)
- "Indirect" ways to determine astrophysical reactions, discussing projects at CRIB:

1. Resonant scattering with thick-target method in inverse kinematics (TTIK)

   Many experiments, ^{7}Li/^{7}Be+α, ^{30}S+α, ^{10}Be+α, ^{15}O+α, etc.

2. Trojan Horse experiments with RI beam (Italy-Japan collaboration)

   ^{18}F(p,α) in Novae (Silvio Cherubini, INFN-LNS)

   ^{7}Be(n,p)/(n,α) in BBN (Seiya Hayakawa, CNS, U-Tokyo)

3. ANC

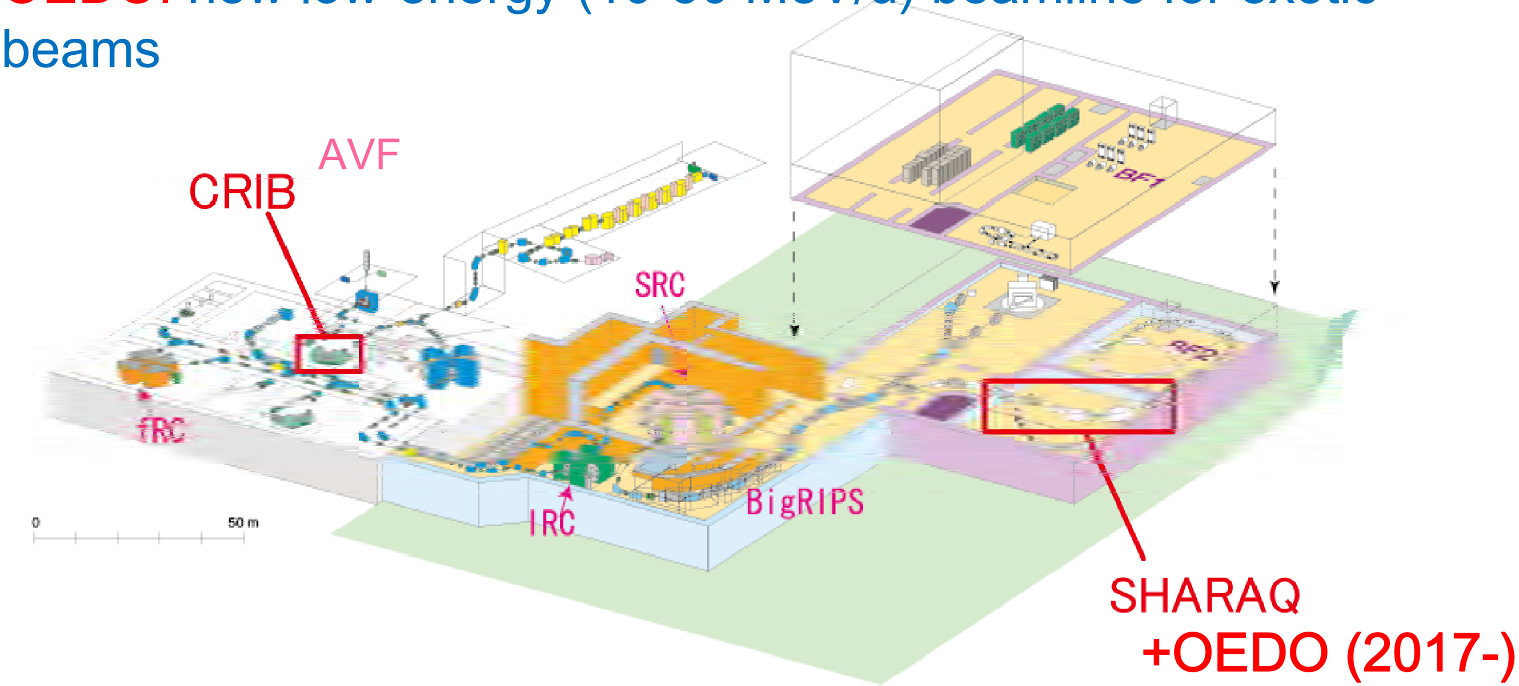
   ^{12}N(p,γ) (B. Guo, CIAE)

   ^{13}N(p,γ) (S. Artemov+R. Yarmukhamedov, INP, Uzbekistan)

CRIB/OEDO in RIBF

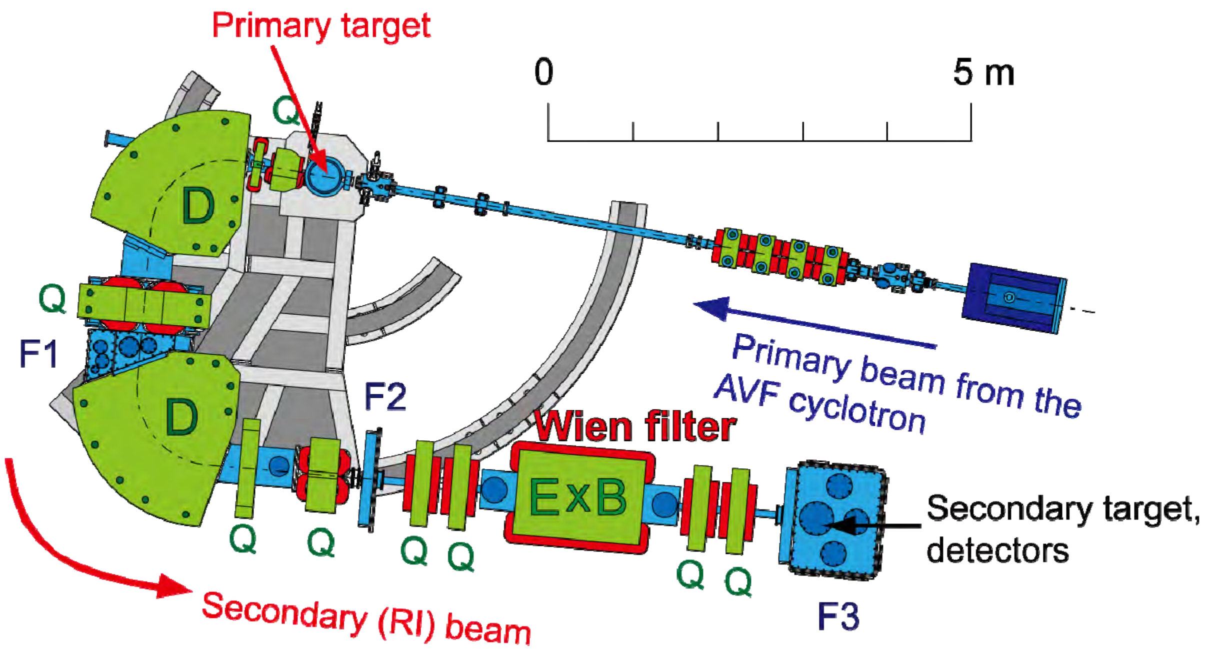
Facilities operated by CNS, the University of Tokyo in RIBF (RIKEN Nishina center)

- CRIB: RI beam separator for low-mass, low-energy (<10 MeV/u) RI beams
- SHARAQ: high resolution spectrometer
- OEDO: new low-energy (10-50 MeV/u) beamline for exotic beams



CRIB

- CNS Radio-Isotope Beam separator , constructed and operated by CNS, Univ. of Tokyo, located at RIBF (RIKEN Nishina Center).
  - Low-energy(<10MeV/u) RI beams by in-flight method.
  - Primary beam from K=70 AVF cyclotron.
  - Momentum (Magnetic rigidity) separation by “double achromatic” system, and velocity separation by a Wien filter.
  - Orbit radius: 90 cm, solid angle: 5.6 msr, momentum resolution: 1/850.

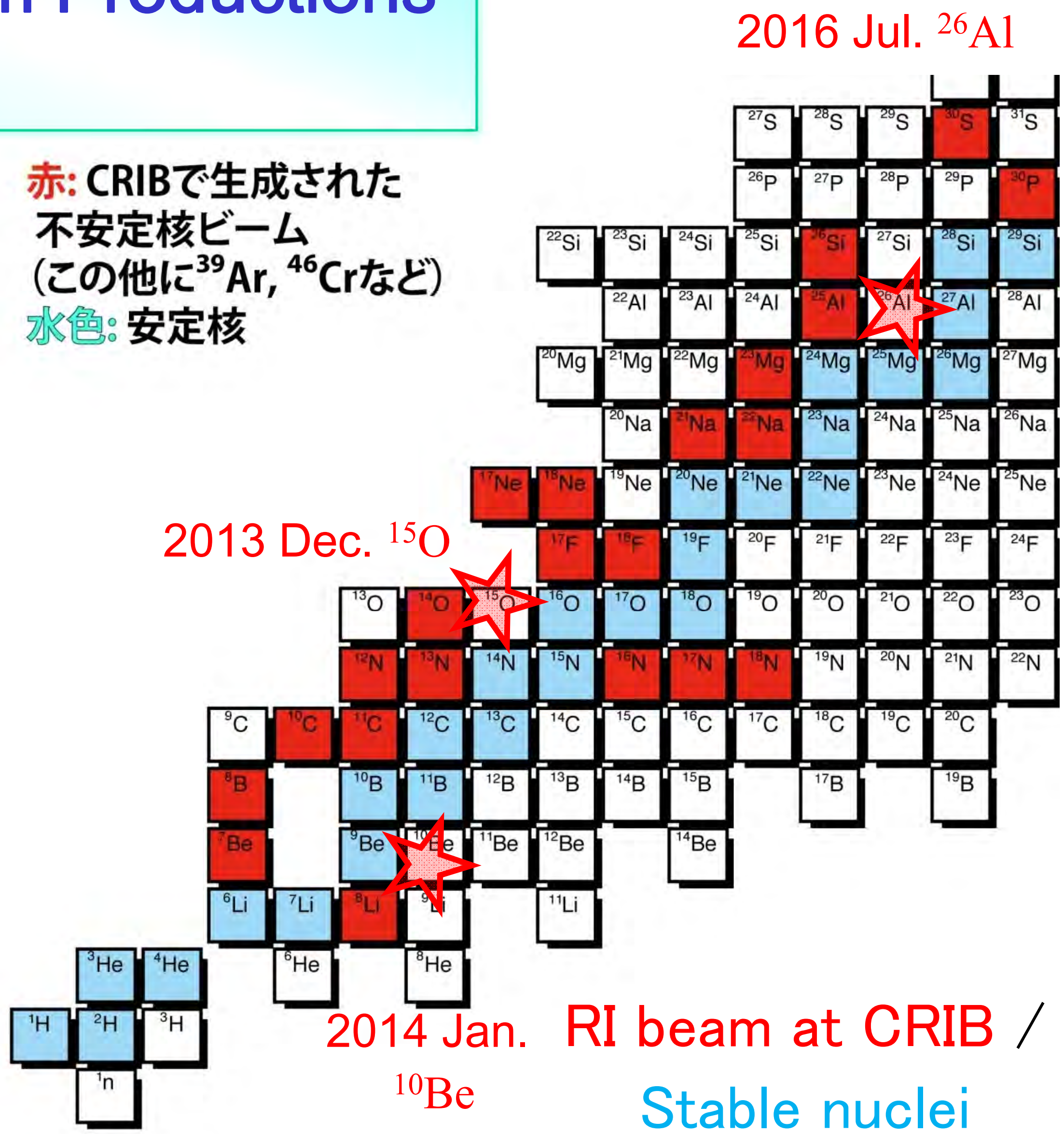


Low-Energy RI beam Productions at CRIB

2-body reactions such as (p,n), (d,p) and (^{3}He,n) in inverse kinematics are mainly used for the production….large cross section

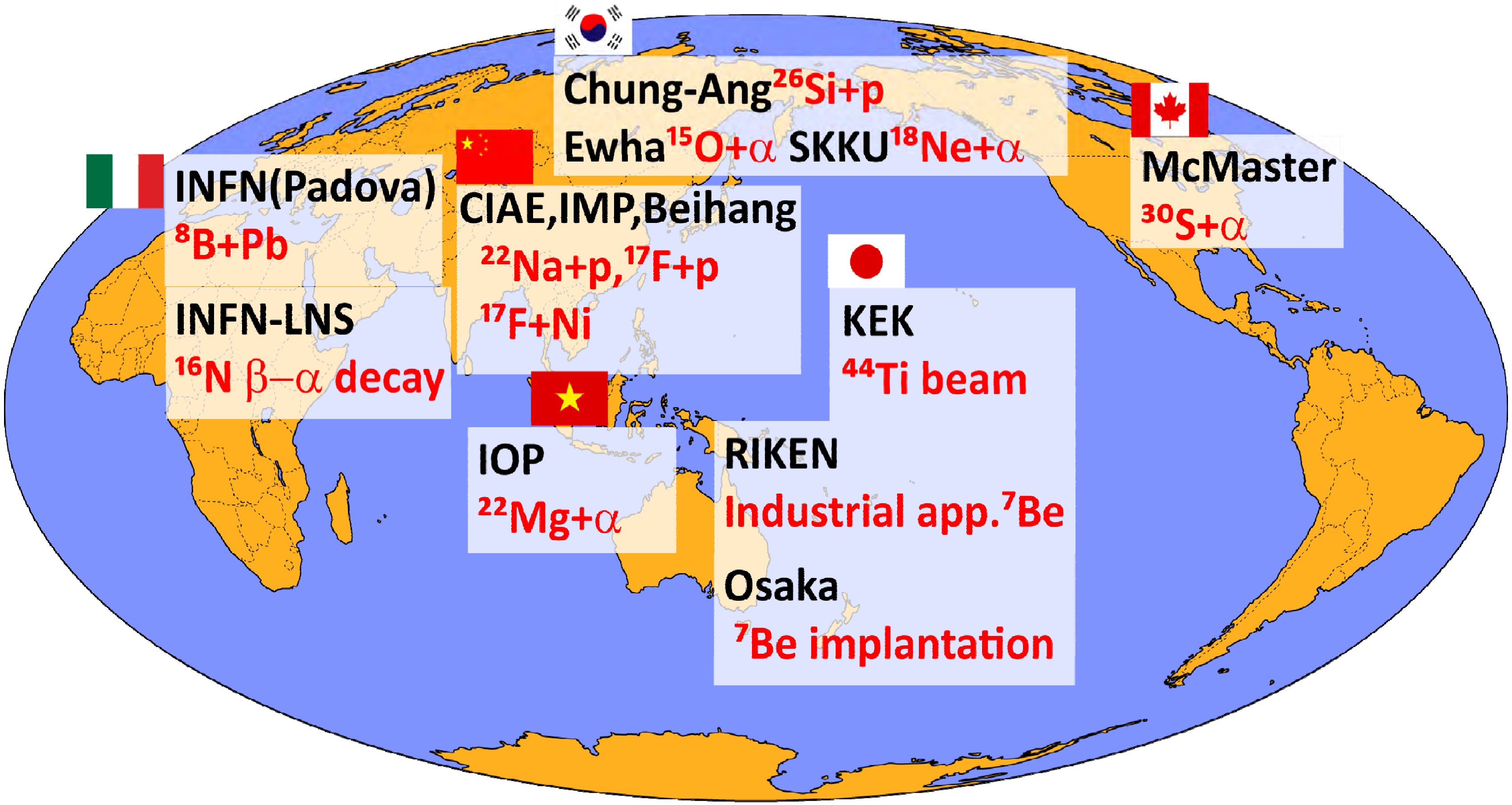
Many RI beams have been produced at CRIB: typically 10^4-10^6 pps

Higher intensity for ^{7}Be beam with cryogenic H_2 target: 3 x 10^8 pps.



CRIB is collaborative

- CRIB experiments during 2010-2016 proposed by external groups:



CRIB is productive …publications since 2011

Proton resonant scattering; astrophysical reactions, galactic γ-ray from ^{26}Al.

^{26}Si+p; H.S. Jung et al., Phys. Rev. C (2012).

^{25}Al+p; Jun Chen et al., Phys. Rev. C(2012), H.S. Jung et al., Phys. Rev. C (2014).

^{21}Na+p; J.J. He et al., Phys. Rev. C (2013), L.Y. Zhang et al., Phys. Rev. C (2014).

^{22}Na+p; S. Jin et al., Phys. Rev. C (2012).

^{17}F+p; J. Hu et al., Phys. Rev. C (2014).

α-resonant scattering; α clustering and (α,γ) reactions

^{7}Li+α/ ^{7}Be+α; H. Yamaguchi et al., Phys. Rev. C (2011 and 2013).

^{30}S+α; D. Kahl, Ph.D. thesis at Univ. of Tokyo (2015), Phys. Rev. C (2018).

^{10}Be+α; H. Yamaguchi et al., Phys. Lett. B (2017).

(α,p) direct reaction measurement

^{11}C(α,p); S. Hayakawa, Dr. thesis at Univ. of Tokyo (2012), Phys. Rev. C (2016).

^{14}O+α; A. Kim et al., Phys. Rev. C (2015).

Indirect astrophysical reaction measurement

^{18}F(p,α); Trojan Horse Method with RI beam S. Cherubini et al., Phys. Rev. C (2015).

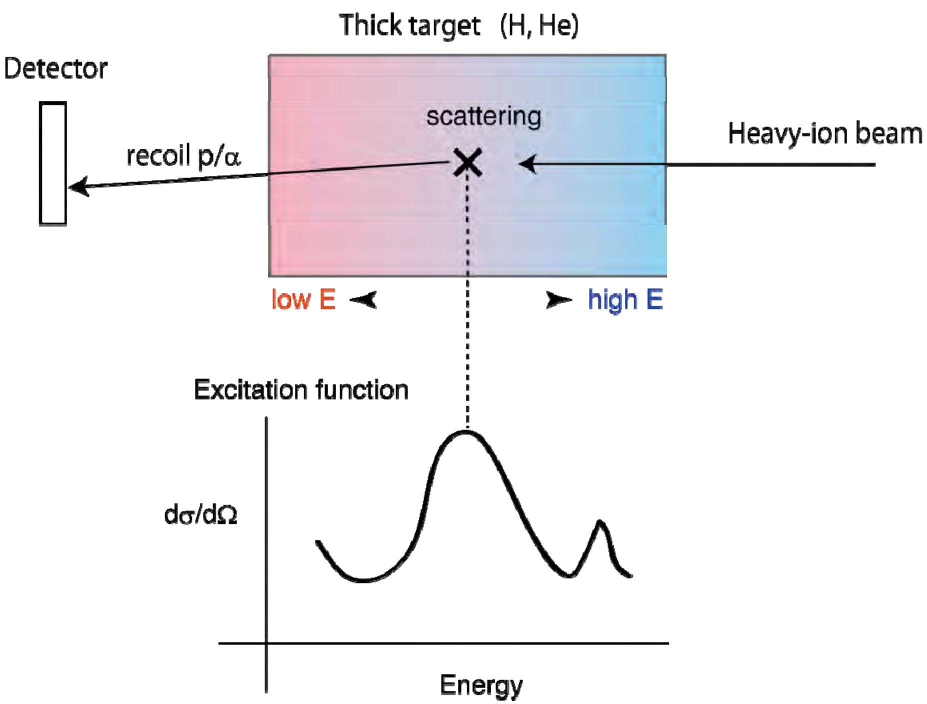
^{12}N(p,γ) by ANC B. Guo et al., Phys. Rev. C (2013).

Reaction mechanism

^{17}F+^{12}C; Quasi-elastic scattering G.L. Zhang et al., Eur. Phys. J. A (2012).

Method: the thick-target method in inverse kinematics

Measurement of resonance scattering



- Inverse kinematics… measurement is possible for short-lived RI which cannot be used as the target.
- Simultaneous measurement of the excitation function for certain energy range.(Small systematic error, no need to change beam energy.)
- The beam can be stopped in the target…measurement at θ_{cm}=180 deg. (where the potential scattering is minimal) is possible.

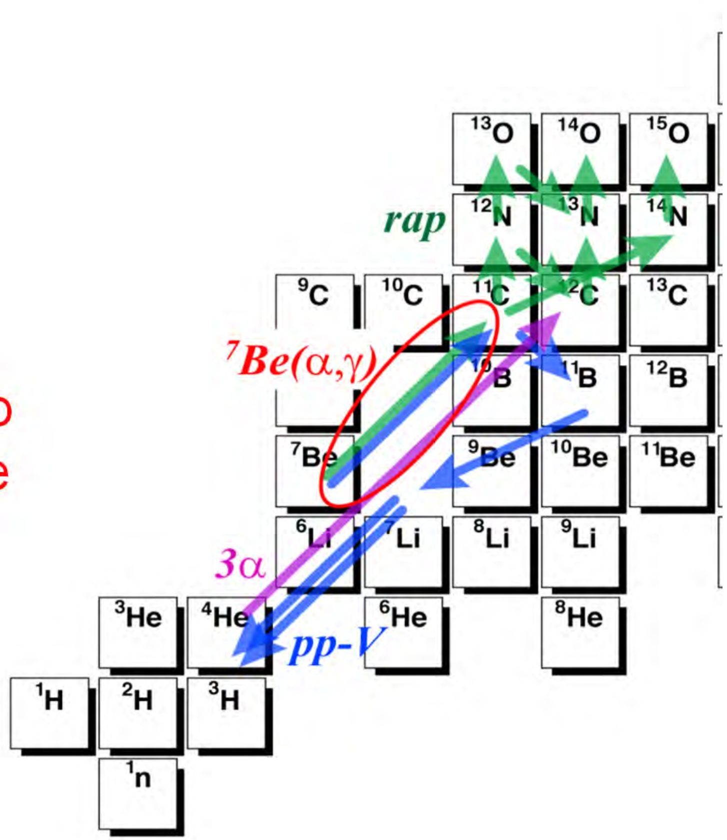
α-resonant scatteing … a striking method to study resonant reactions and nuclear clusters

1. ^{7}Li+α (^{11}B), 3-body cluster, neutrino process (H. Yamaguchi et al., Phys. Rev. C (2011).
2. ^{7}Be+α (^{11}C), mirror symmetry between ^{11}B and ^{11}C, supernovae nucleosynthesis H. Yamaguchi et al., Phys. Rev. C (2013).
3. ^{10}Be+α (^{14}C), Linear-chain levels H. Yamaguchi et al., Phys. Lett. B (2017).
4. ^{30}S+α (^{34}Ar), astrophysical ^{30}S(α, p) reaction (D. Kahl et al., Phys. Rev. C (2018).
5. ^{15}O+α (^{19}Ne), Comparison with ^{20}Ne cluster, astrophysical ^{18}F(p, α) reaction Exp. done in 2015, Kim Dahee Ph.D (2018).
6. ^{18}Ne+α (^{22}Mg), Mirror symmetry breaking? (⇔^{22}Ne) Exp. Done in 2016.

^{7}Li+α/ ^{7}Be+α study

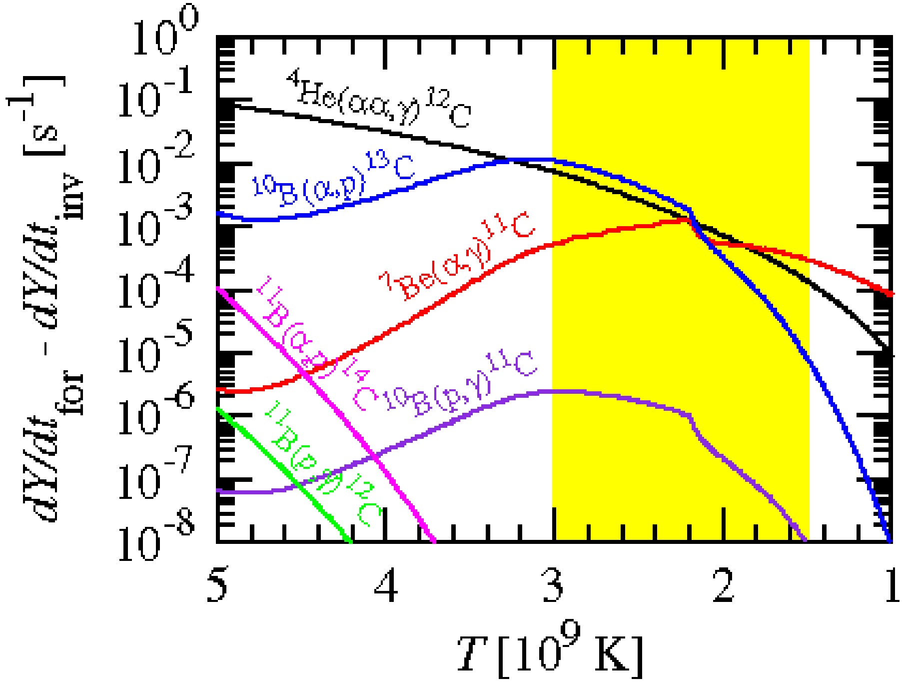
- $^{7}Li(\alpha,\gamma)^{11}B$ …important at high-T, as a production reaction of ^{11}B (the ν-process in core-collapse supernovae).
- $^{7}Be(\alpha,\gamma)^{11}C$ … one of the reaction in hot *p-p* chain, relevant at high-T.

- α-cluster structure in ^{11}B/^{11}C :
  - 2α+*t* / 2α+^{3}He cluster states are known to exist (similar to the dilute cluster structure in ^{12}C.)
  - Several "bands" which have α-cluster structure could be formed. [Our another study topic.]



$^7Be(\alpha,\gamma)$ in supernovae

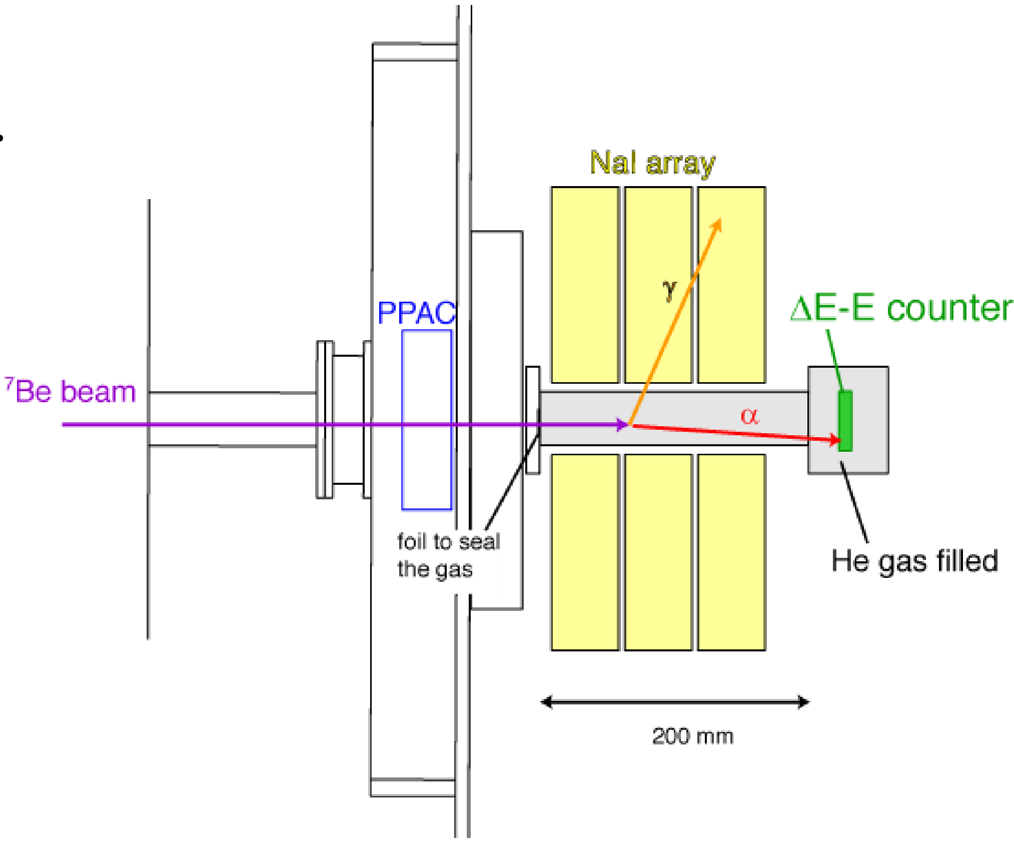
νp-process calculation (T_9>1) shows considerable contribution by $^{10}B(\alpha,p)^{13}C$ and $^7Be(\alpha,\gamma)^{11}C$ as much as the triple-alpha process.



S. Wanajo et al., Astrophys. J (2010)

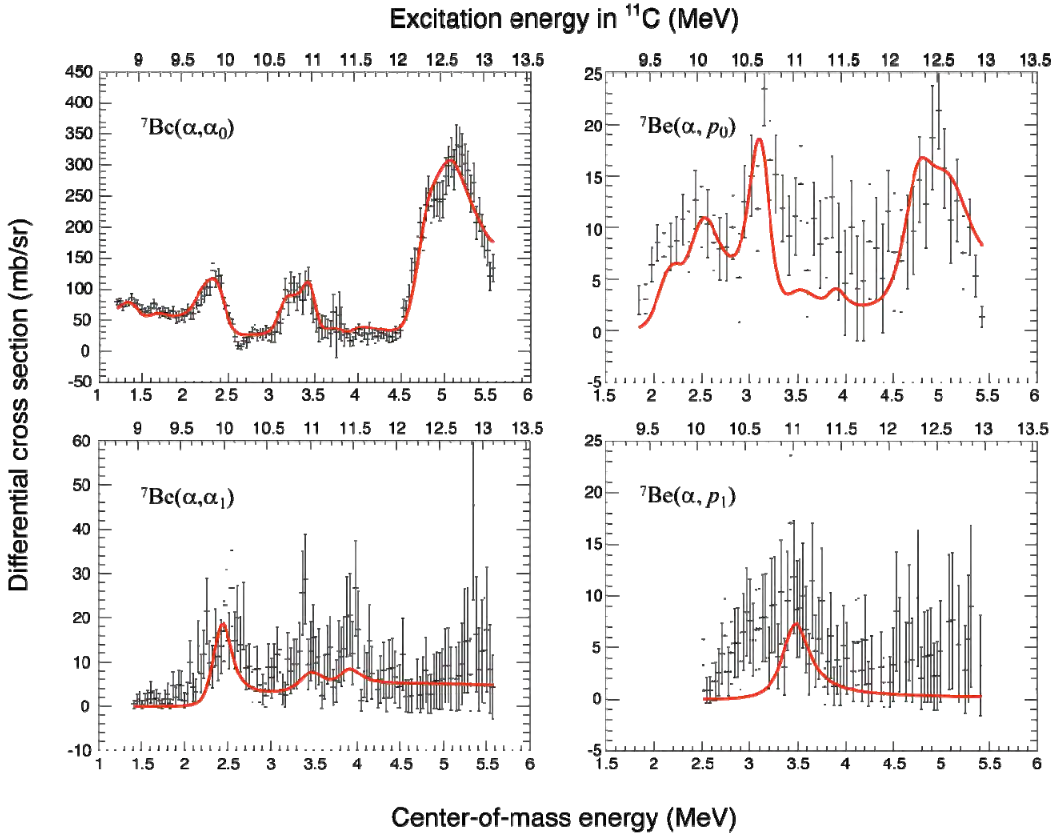
Setup for ^{7}Li/^{7}Be+α

- Thick target method with inverse kinematics …An efficient method to measure excitation function.
  - ^{7}Be beam is monitored by a PPAC (or an MCP detector).
  - ^{7}Be beam stops in a thick helium gas target (200 mm-long, 1.6 atm).
  - Recoiled α particles are detected by ΔE-E counter (10 μm and 500 μm Si detectors) at forward angle.
  - NaI array for γ-ray measurement (to identify inelastic events).



^{7}Be+α Excitation functions

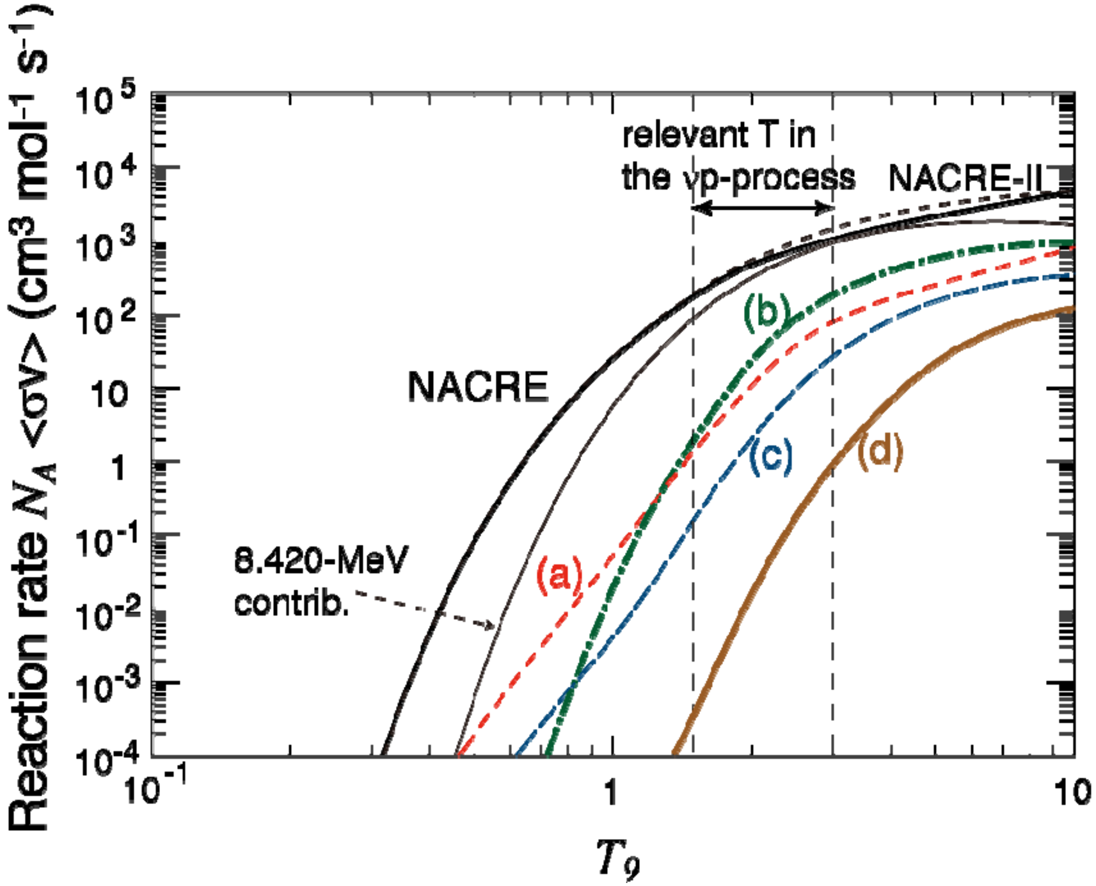
- 4 excitation functions… new information on resonant widths, spin, and parity. *H. Yamaguchi et al., PRC (2013).*



^{10}B(p,α)… See *Wiescher et al.,PRC **95**,044617(2017).*

Resonant contribution to $^{7}Be(\alpha,\gamma)$

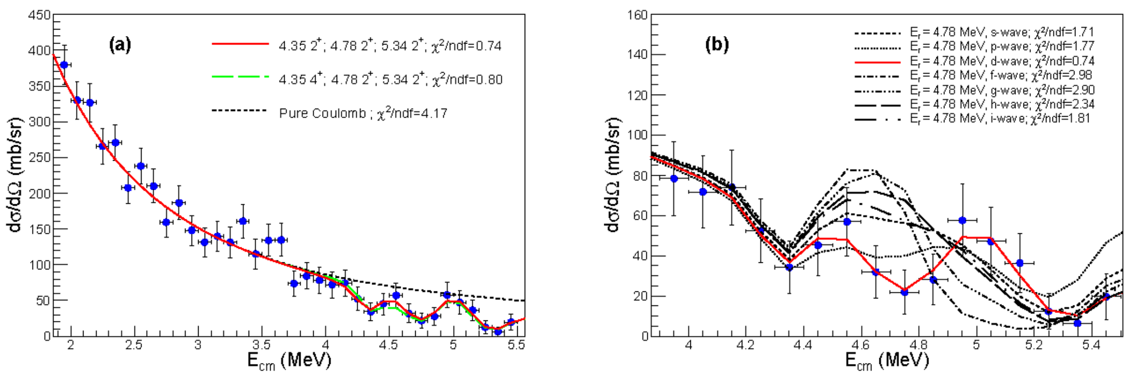
- Small but not negligible contribution compared to lower-lying states (~10%).



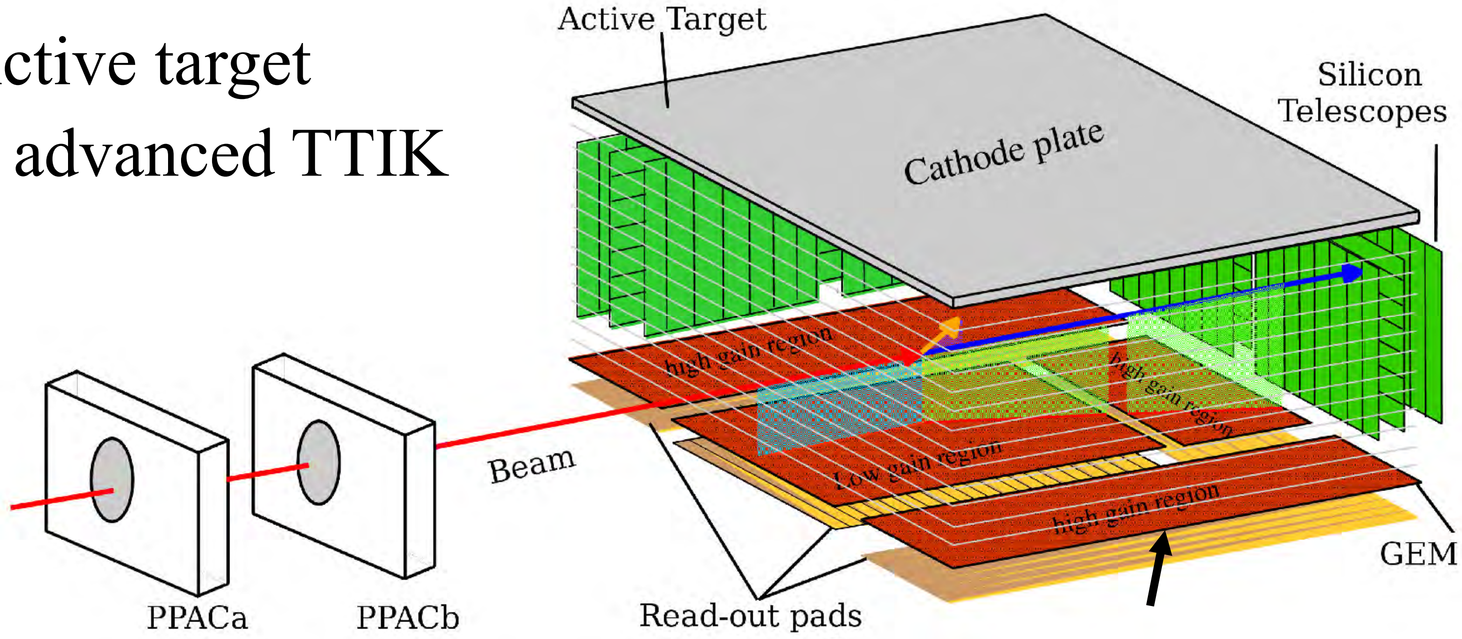
^{30}S(α,p)

- ^{30}S(α,p) … one of the key reaction in X-ray bursts.
- Scarce ^{34}Ar resonance information, reaction rate evaluation was only by statistical model.

- ^{30}S+α resonant scattering with active target D. Kahl et al., Phys. Rev. C (2018).
- 3 higher-lying resonances were observed:



Active target
for an advanced TTIK



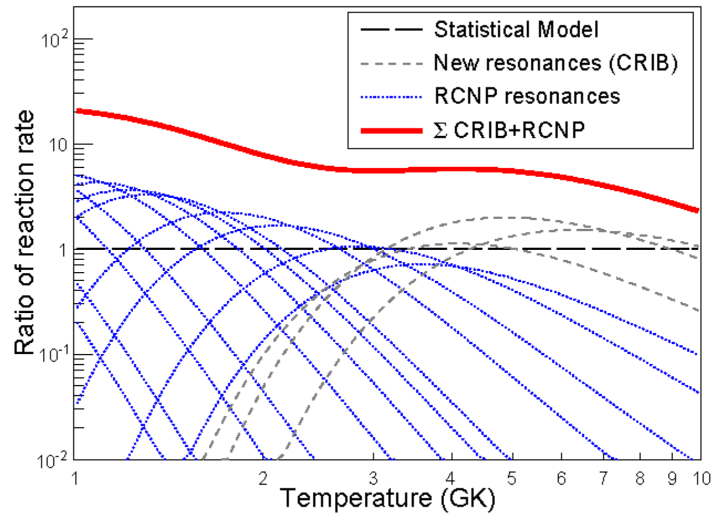
He (90%) +CO_2 (10%)
mixture gas(160 torr)

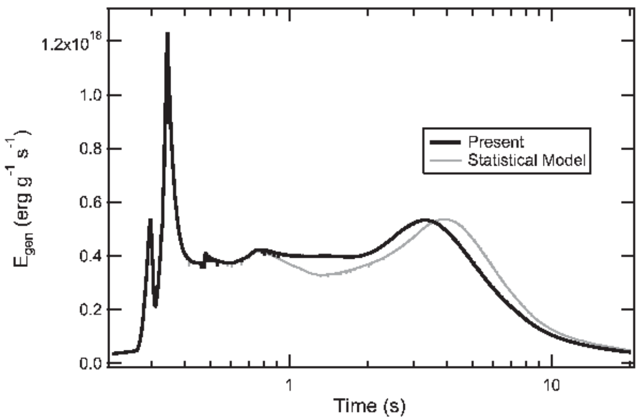
- Acts as a He target and a detector (TPC) simultaneously
- GEM with "backgammon" type readout pad.
- 3-dimentional trajectory and energy loss can be measured
  ⇒ Accurate event identification.

Astrophysical implications

Reaction rate (upper limit) evaluation with RCNP(Osaka) $^{36}Ar(p,t)^{34}Ar$ transfer reaction data + **CRIB(Tokyo) resonant scattering data**

⇒Higher than the stat. model rate calculation





⇐X-ray burst energy generation higher than the statistical model:

25% enhancement [even with this single reaction].

-Max. 30% of abundance change for A=20-80 nuclei.

The origin of galactic ^{26}Al gamma rays

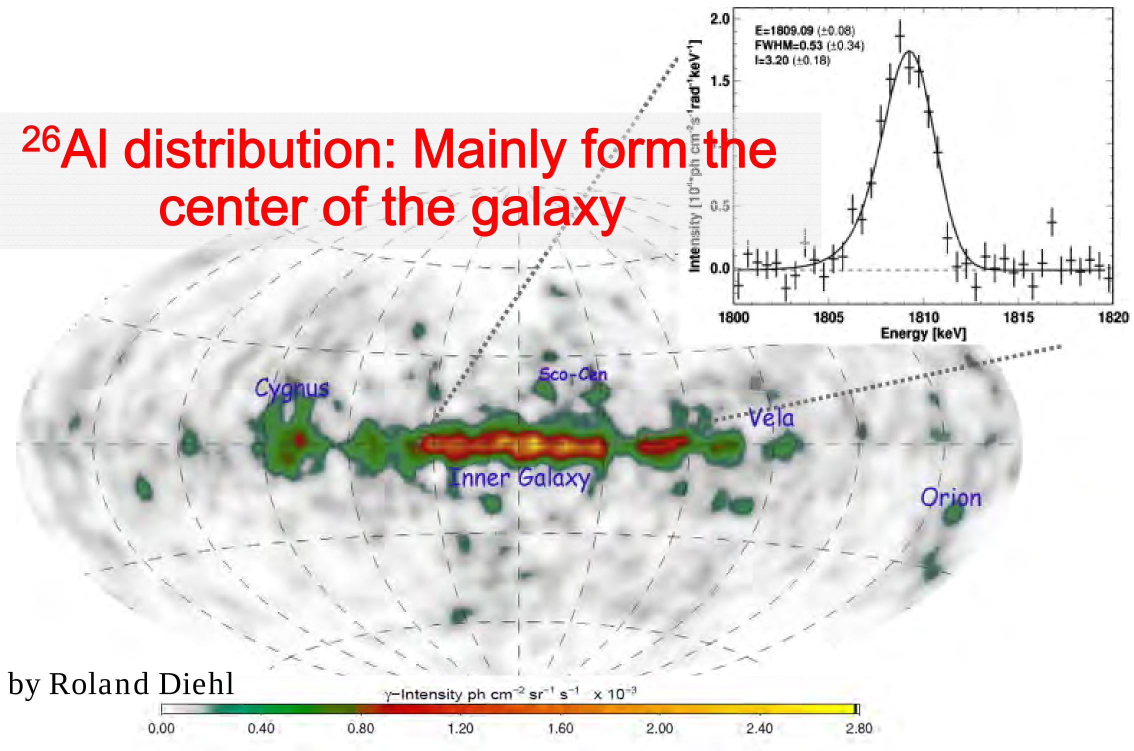
^{26}Al γ–ray : **The first observed** cosmic γ–ray from specific nuclide (1.809 MeV)

An evidence of the on-going nucleosynthesis.

A key for understanding the evolution of the galaxy ($^{26}Al^{gs}$, $t_{1/2}$ = 0.7 million years)

Production source: still uncertain. Massive stars? Supernovae? Novae?

^{26}Al distribution: Mainly form the center of the galaxy



Too much ^{26}Al

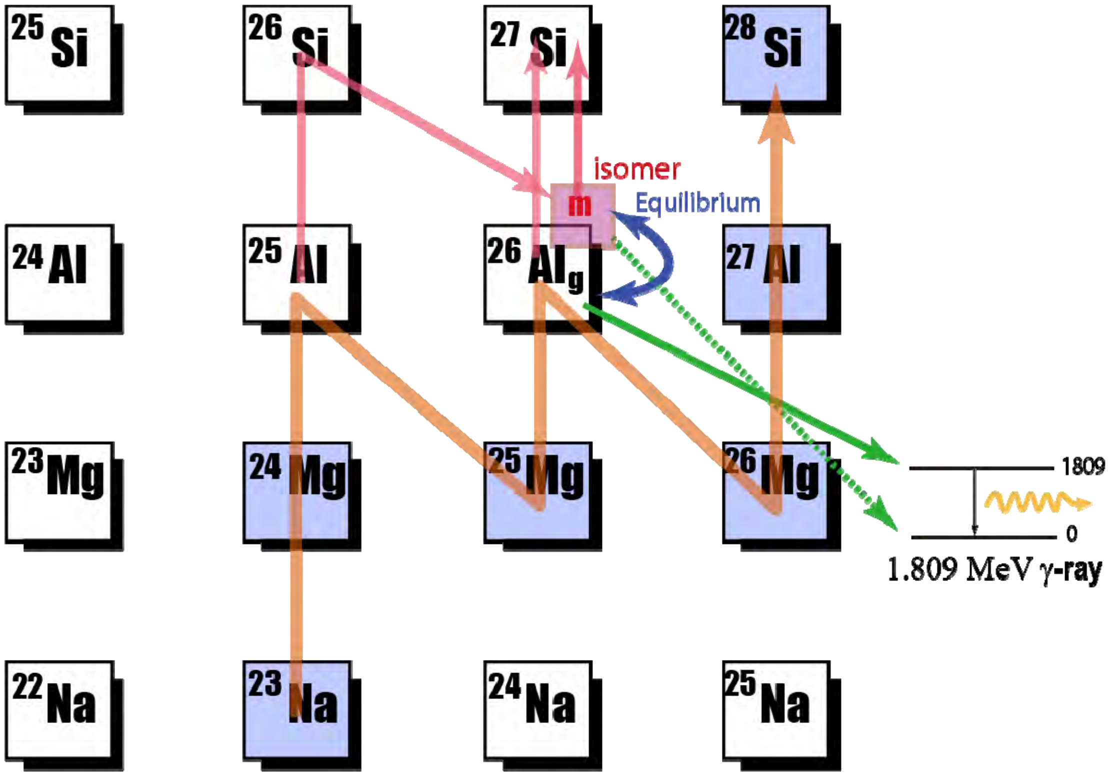
2.0 ± 0.4 $M_\odot$ – Diehl (2016),

but

> 3$M_\odot$ expected from ccSN, WR, AGB and SAGB simulation.

Needs ^{26}Al-destruction process?

26Al



High-T (>> 0.4GK)

Isomeric ^{26}Al does not produce γ-rays, however,

- ^{26m}Al production by ^{25}Mg(p,γ) and also from ^{25}Al⇒^{26}Si decay.
- Thermal equilibrium between ^{26g}Al and ^{26m}Al.
- ^{26}Al(p,γ)^{27}Si reaction destroys ^{26}Al.

^{26}Al isomer beam

- ^{26}Mg(p,n)^{26}Al reaction: At the energy of CRIB, the maximum angular momentum brought by the beam is limited, and the production of ^{26}Al ground state(5^+) is highly suppressed. ⇒High purity ^{26}Al isomer beam production is possible.
- This seemed to be a unique idea in 2014, but…

^{26}Al^m beam @Argonne:

S. Almaraz-Calderon et al., Phys. Rev. Lett 119, 072701 (2017), B.W. Asher et al., NIM A (2018).

At CRIB:

2016 First ^{26m}Al beam production

2017 ^{26m}Al+p resonant scattering measured

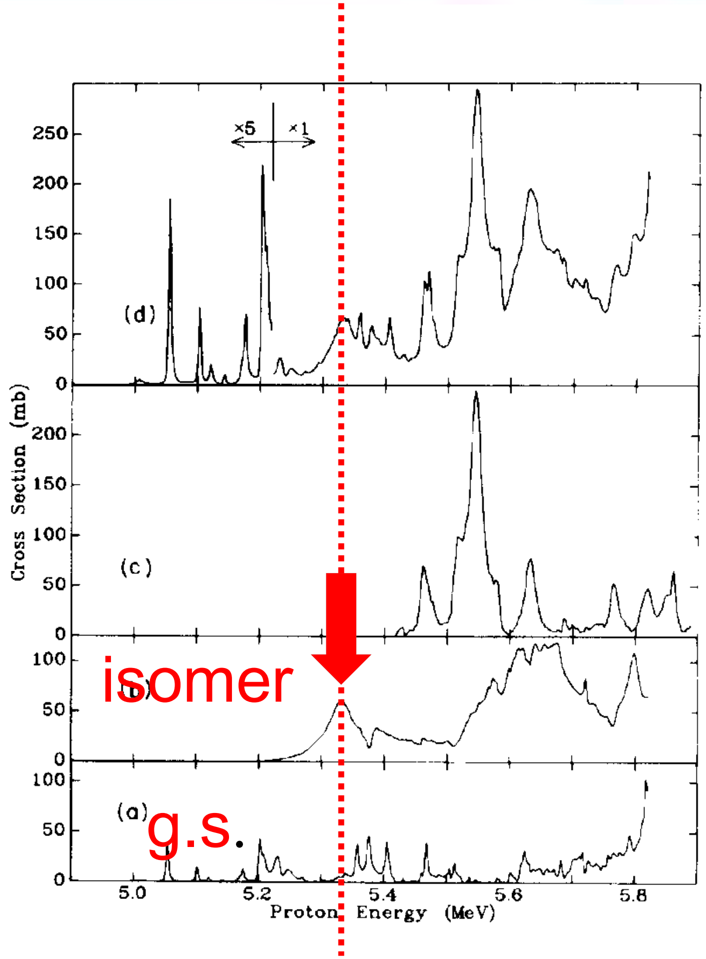
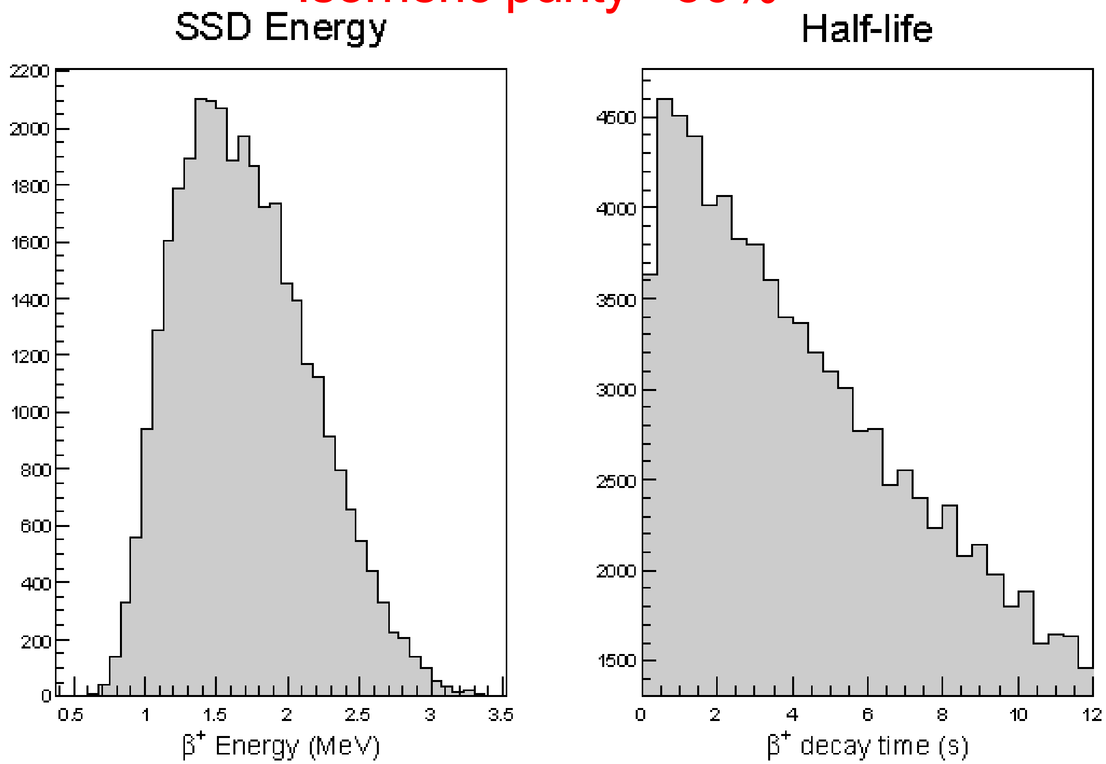


FIG. 4. Excitation functions for (a) ^{26}Mg(p,n_0)^{26}Al, (b) ^{26}Mg(p,n_1)^{26}Al, (c) ^{26}Mg(p,n_2)^{26}Al, and (d) the total neutron yield.

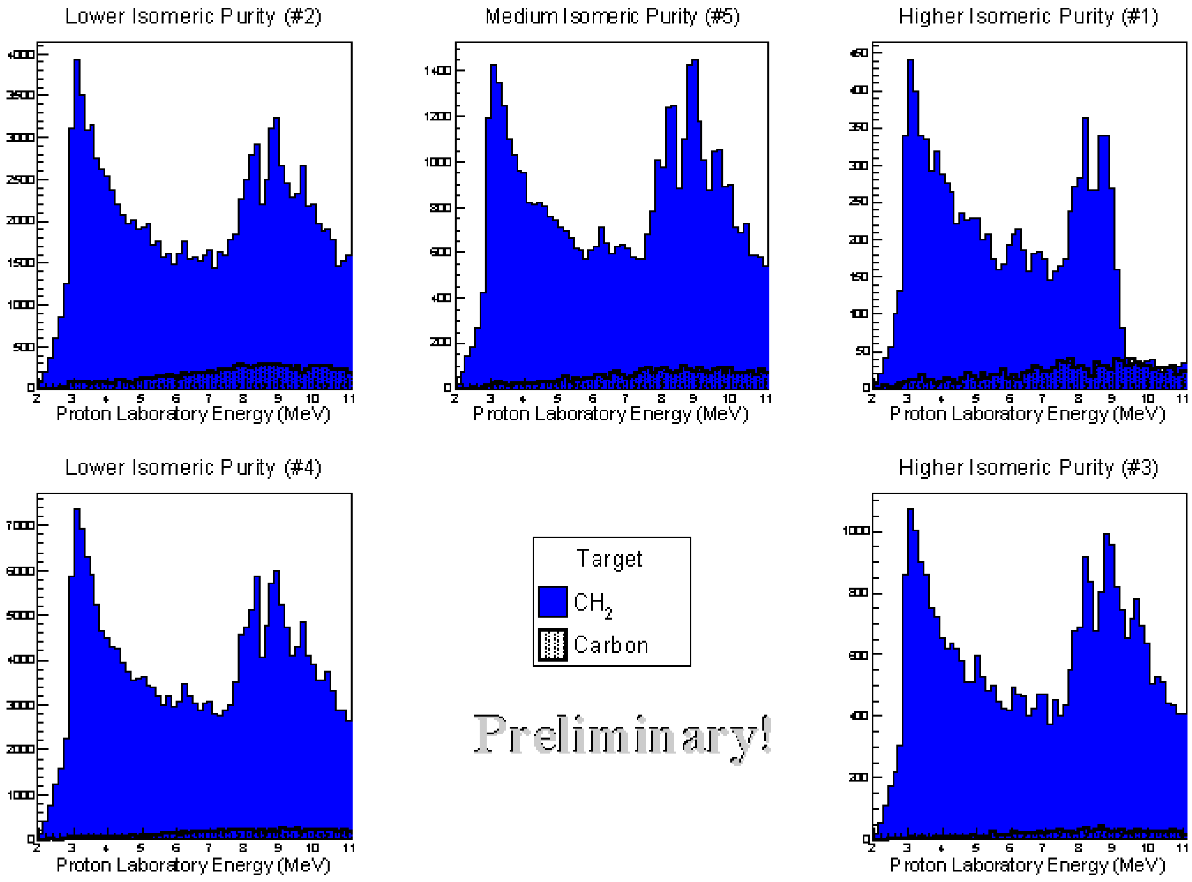
Proof we made ^{26m}Al

- Pulsed the beam in regular tests, 12 s on – 12 s off
  - Measured the β^+'s with the Si telescope
  - (Also measured 511-keV γ's with NaI)
    - Isomeric purity ~50%



β^+ decay measurements: (a) Energy spectrum and (b) Decay timing. Both are consistent with ^{26m}Al.

^{26}Al proton spectra – the method worked!



Rough normalization (factor 2 error). Clear evidence of structure arising from ^{26m}Al and not ^{26g}Al.

The $^{18}F(p,\alpha)$ project (THM)

- $^{18}F(p,\alpha)$… an astrophysical reaction important in novae, and other high-T environments.

- Measurement with the Trojan Horse Method performed in 2008

…**The first THM+RI beam experiment in the world.**

- The RI Beam at CRIB (after development):

Primary beam: $^{18}O^{8+}$, 4.5-5 MeVA

Production target: H_2

Production reaction: $^{18}O(p,n)^{18}F$

◆ Purity nearly 100%

◆ Intensity > 5 x 10^5 pps

A NOVA MICKEY MOUSE PICTURE AND $^{18}F(p,\alpha)^{15}O$

Thin hydrogen surface layer accumulated on white dwarf through accretion ring

Observed γ- rays come from e^+e^-

e^+ come from ^{18}F decay mostly

At novae temperatures (100 - 500 keV) ^{18}F can be mainly destroyed by

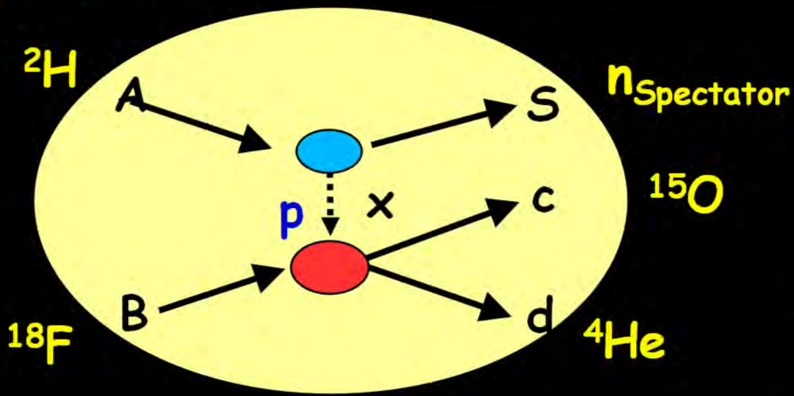
$^{18}F(p,\alpha)^{15}O$

Slides by S. Cherubini

For the star energetics this is peanuts!

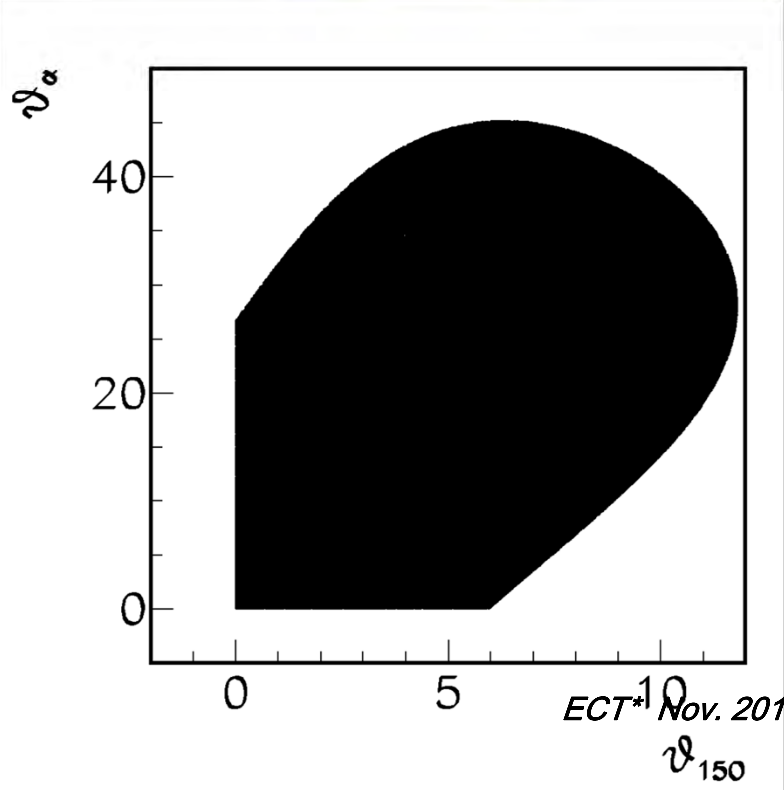
THM measurement: $^{18}F(p,\alpha)^{15}O$ via $^{2}H(^{18}F,\alpha\,^{15}O)n$

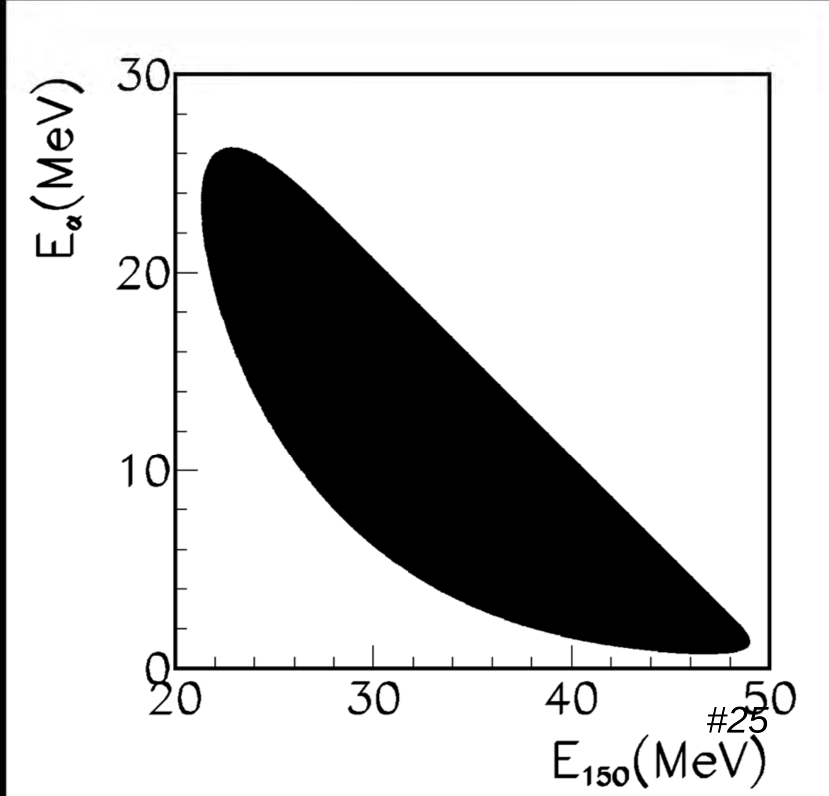
Kinematics



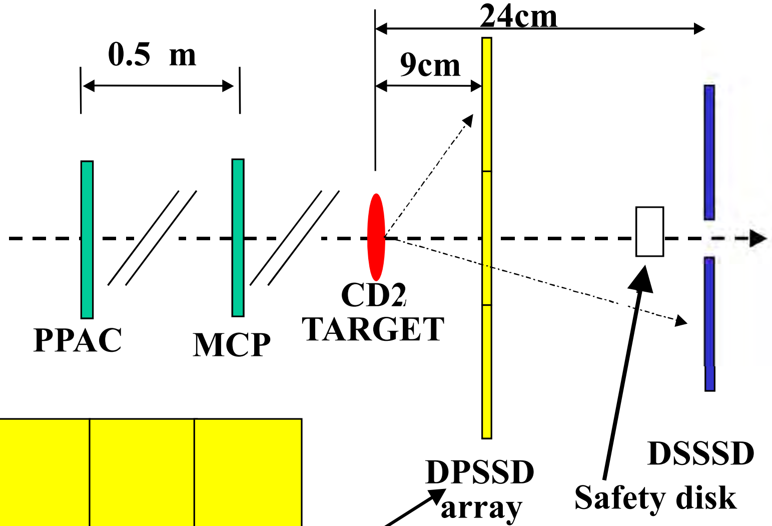
$^{2}H(^{18}F,\alpha\,^{15}O)n$

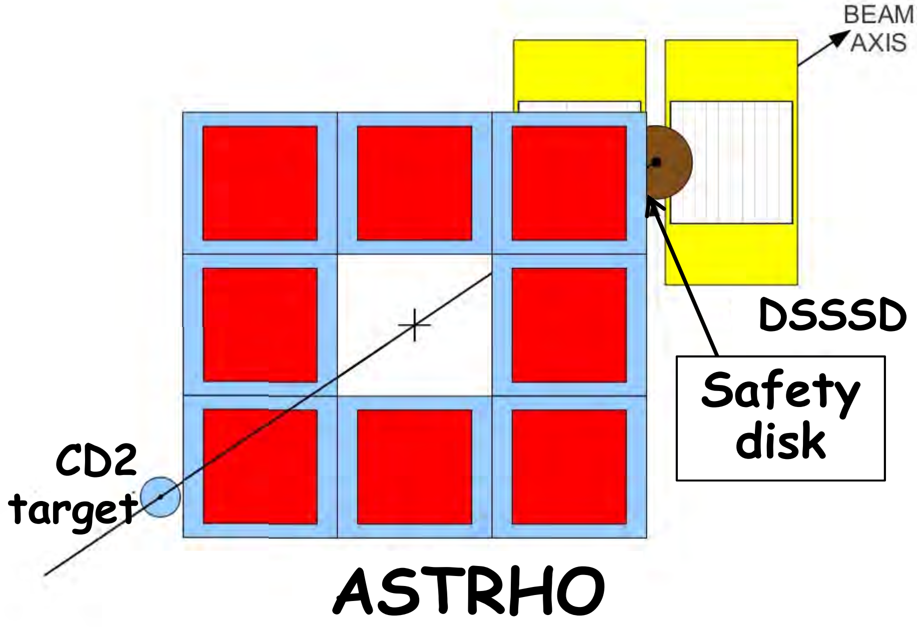
$E(^{18}F) = 50$ MeV

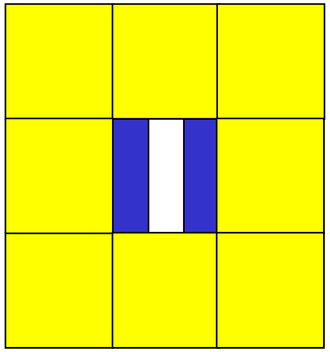




EXPERIMENTAL SETUP







ASTRHO:
Array of Silicons for
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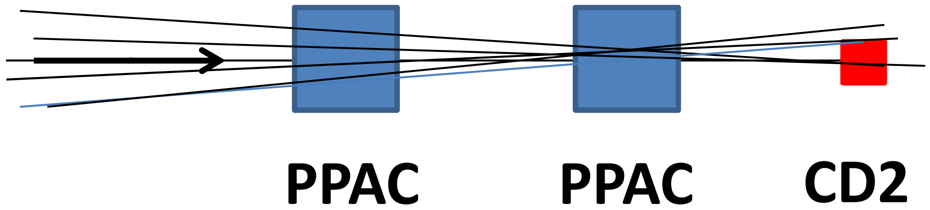


Beam track reconstruction

EVENT SELECTION

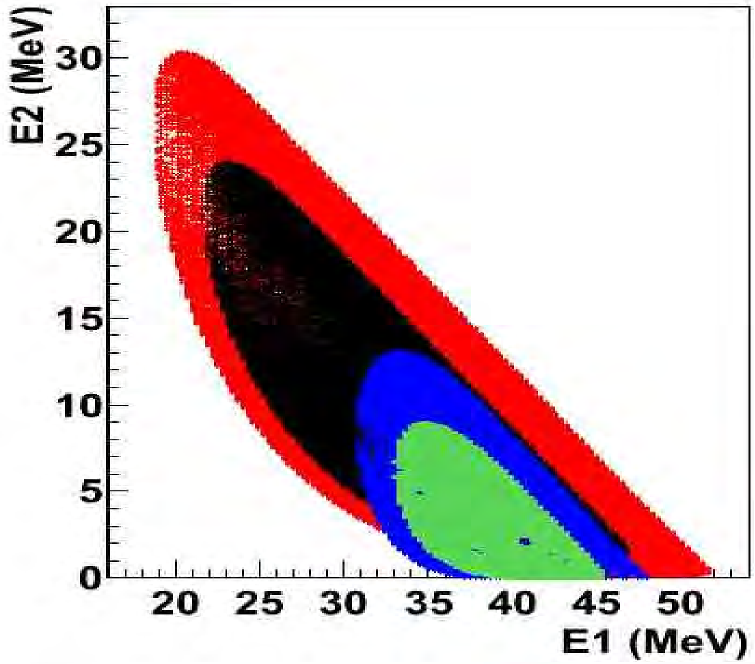
Red: $^{18}F + d \rightarrow {}^{15}N + \alpha + p$

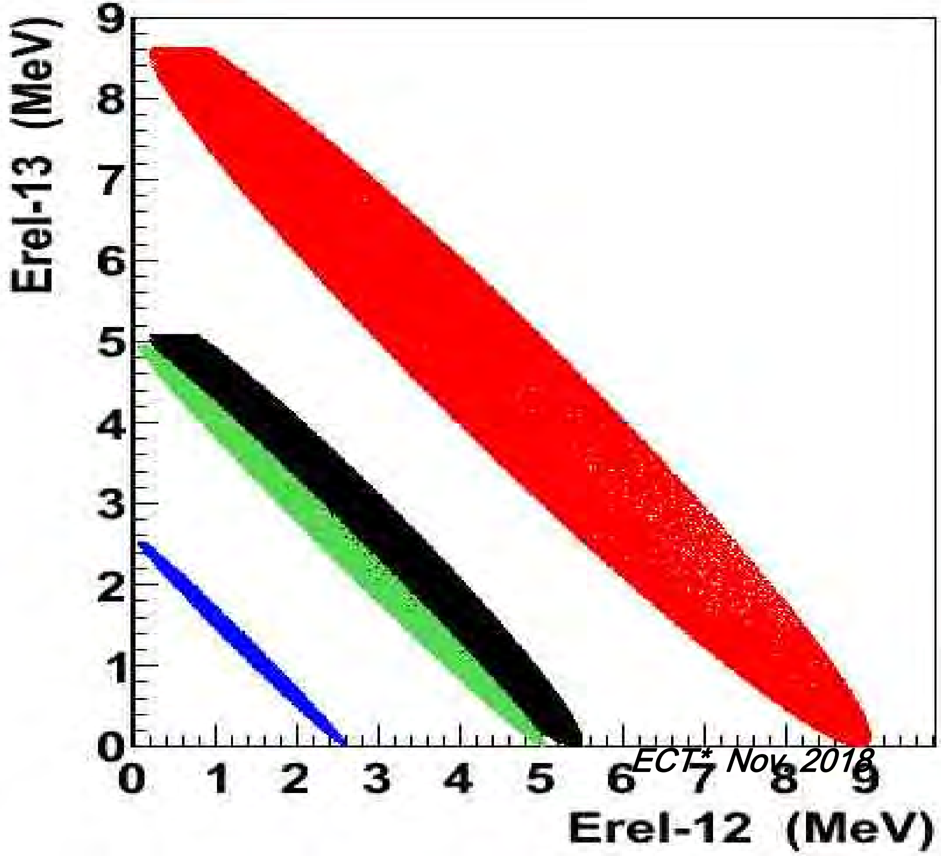
Black: $^{18}F + d \rightarrow {}^{15}O + \alpha + n$

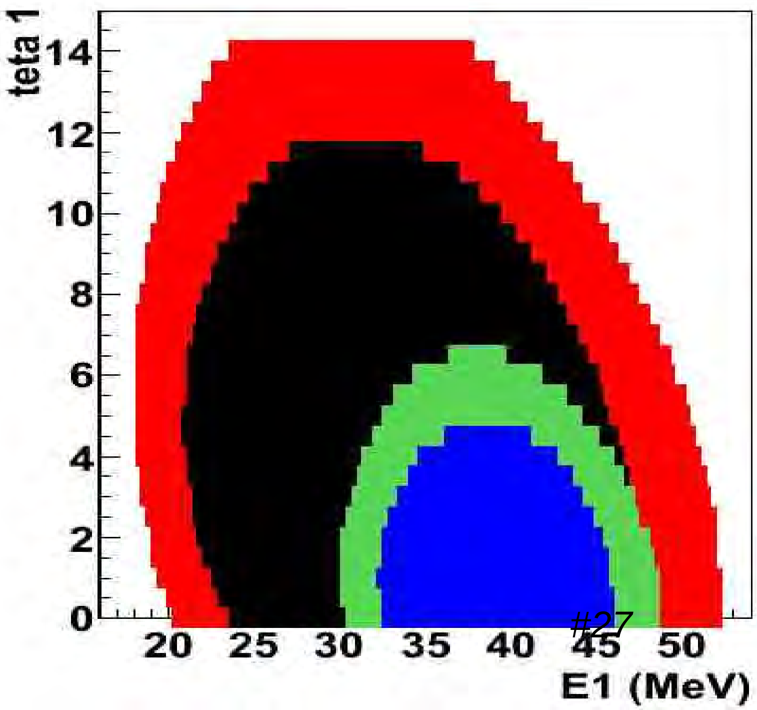
Blue: $^{18}F + d \rightarrow {}^{18}F + p + n$

Green: $^{18}F + d \rightarrow {}^{18}O + p + p$

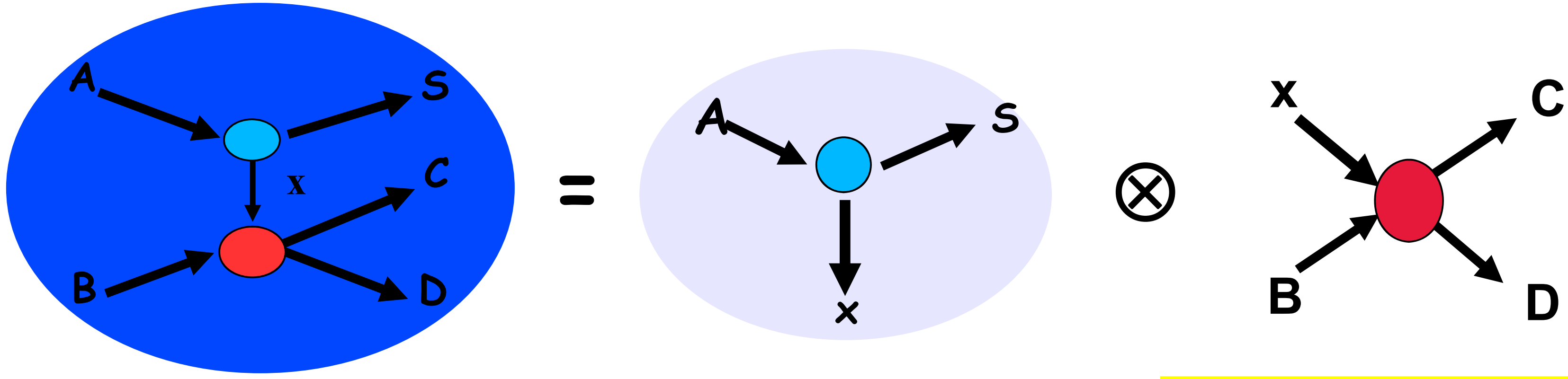
» 1 + 2 + 3







Assuming that a Quasi-free mechanism is dominant one can use the (PW)IA:



3-body Reaction

Virtual Decay

Virtual reaction (astrophysical process)

$$\frac{d^3\sigma}{d\Omega_C\, d\Omega_D\, dE_{cm}} \Big/ KF\cdot|\Phi(P_s)|^2 \propto \frac{d\sigma^N}{d\Omega}$$

Measured at high energy

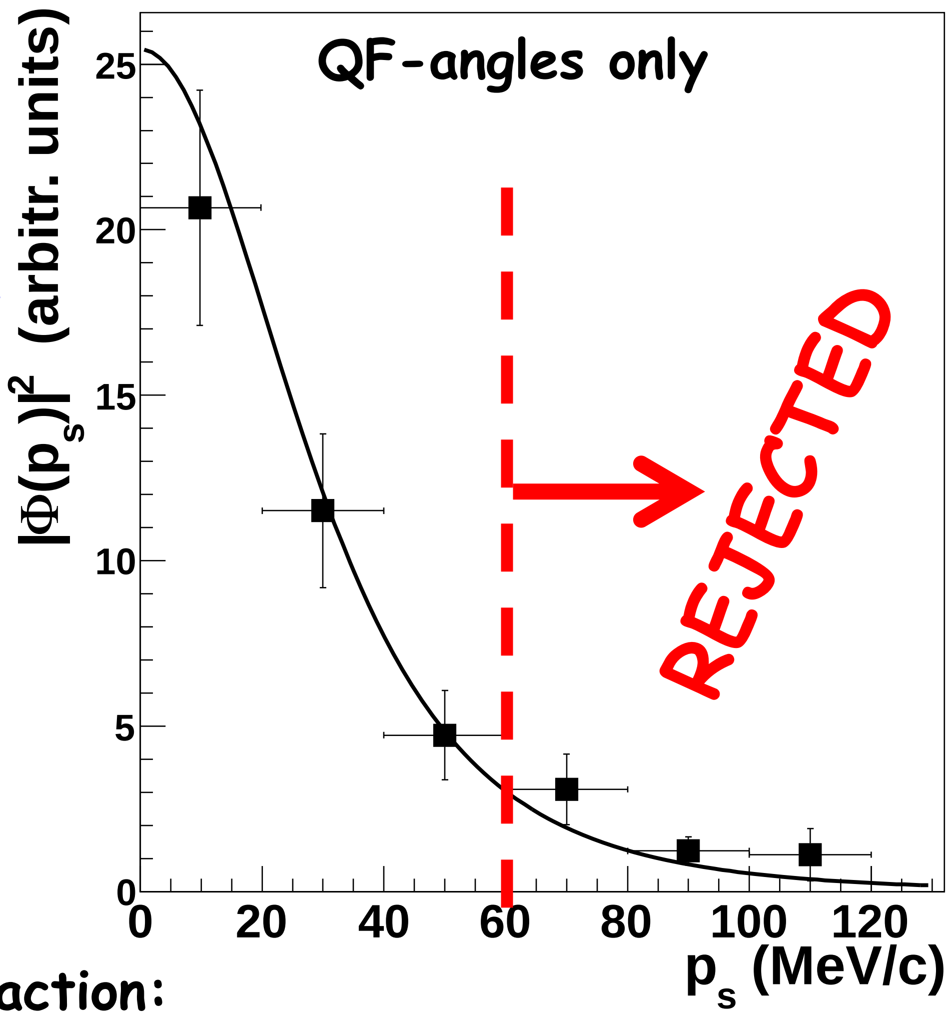
Calculated e.g. Montecarlo

Indirectly Measured

$E_{Bx} = E_{CD} - Q_{2b}$

EXPERIMENTAL IMPULSE DISTRIBUTION

QF channel Seems to be there!



■ Experimental data

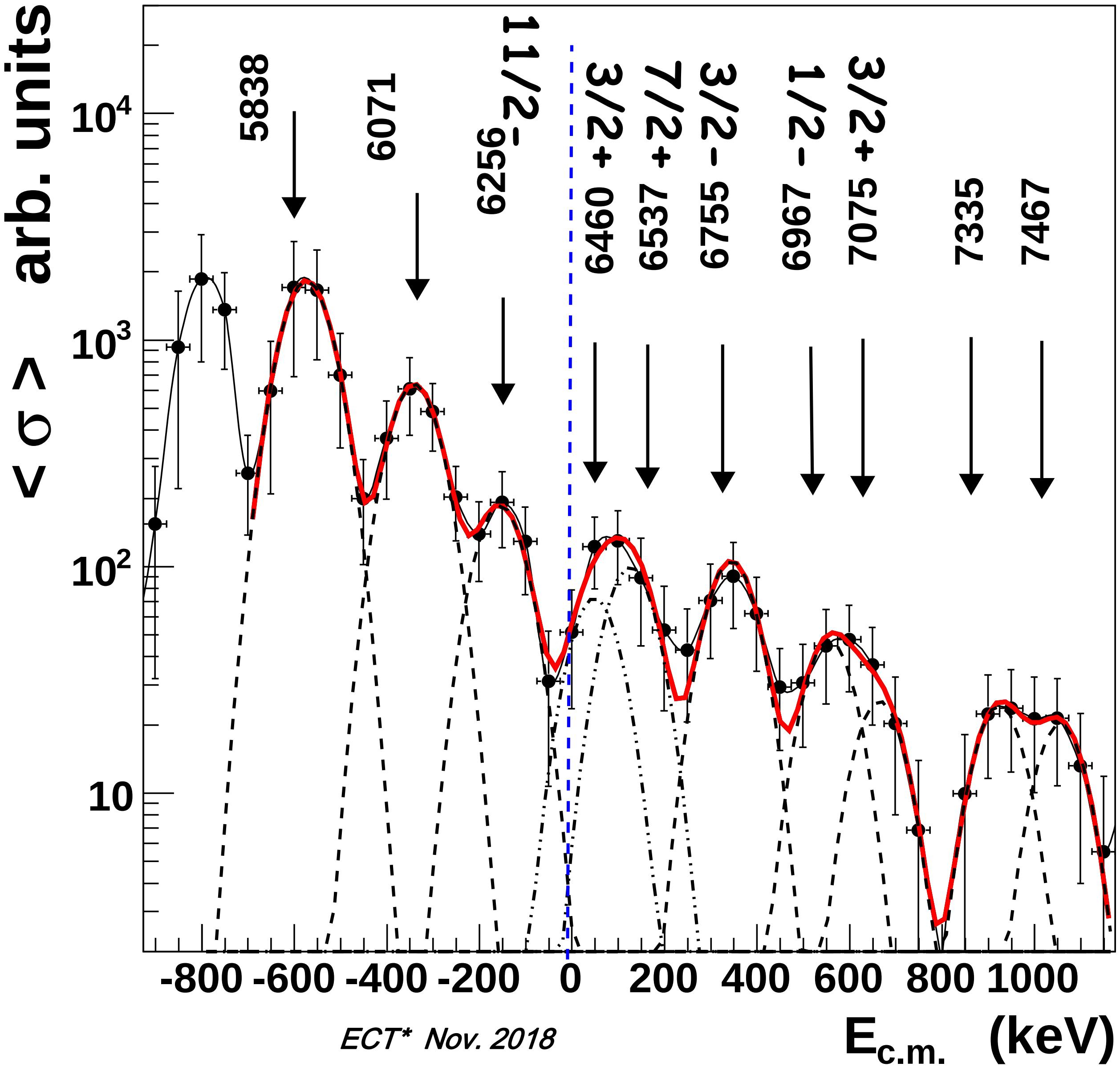
—— Hultén function

If in 2 body Reaction:

Ecm= const

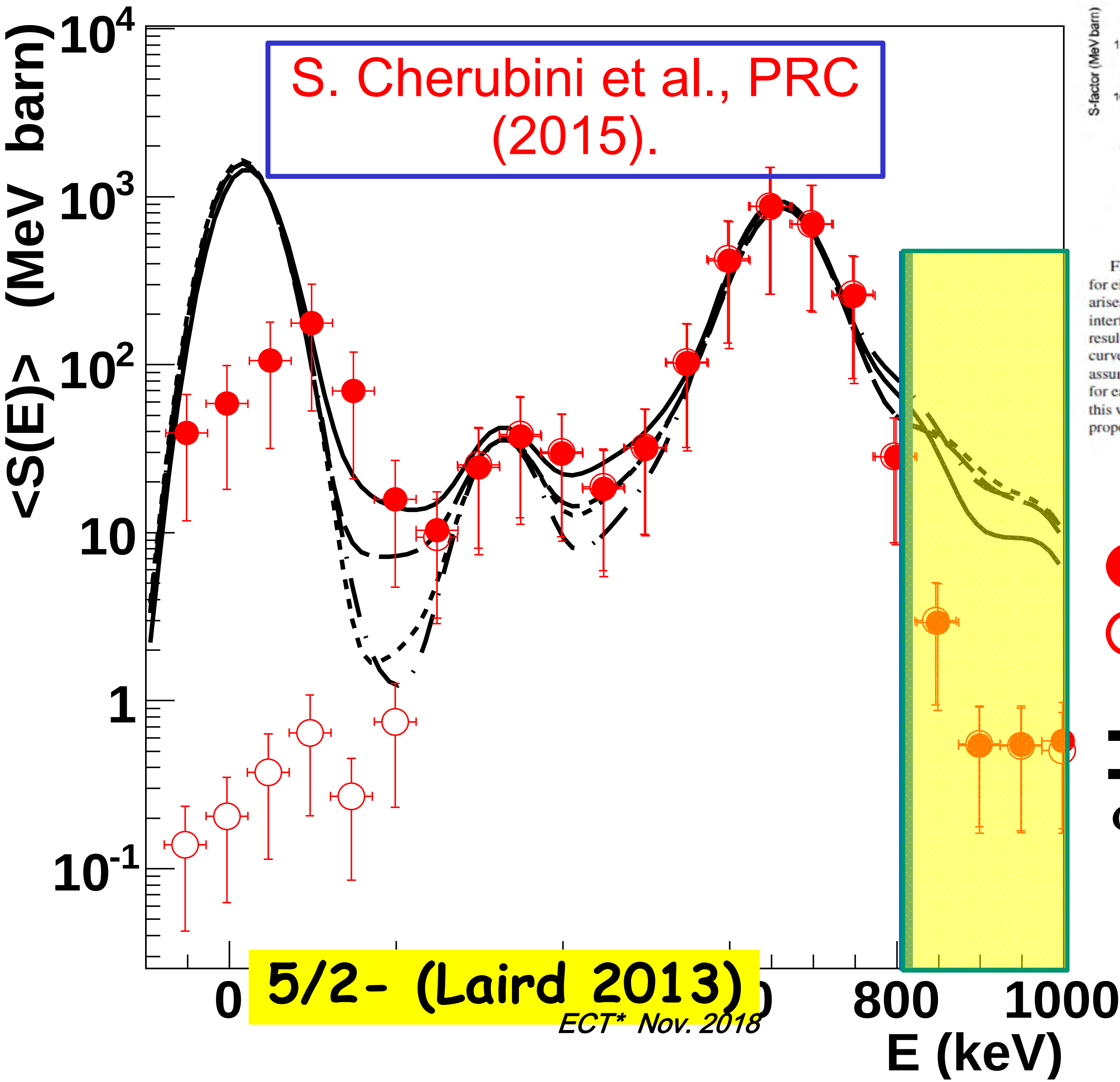
Θcm =const ➡ d2σ/dΩ = const ➡ d3σ/dΩ ∝ $|\Phi(P_s)|^2$

THM(=barriers free) CROSS SECTION



ECT Nov. 2018*

S(E) from THM 8 keV 3/2+



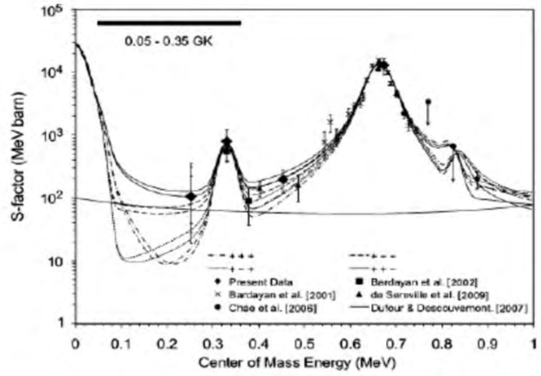


FIG. 3. The $^{18}F(p,\alpha)^{15}O$ S factors, calculated using the R matrix, for eight possible interference terms. The range in possible S factors arises from the interference between the $J^{\pi} = 3/2^{+}$ resonances. The interference between resonances dominates in the region of interest, resulting in four groups of S-factor curves. The upper and lower curves of each group are shown in the figure. The legend gives the assumed phase, for the 8-, 38-, and 665 keV resonances, respectively, for each pair of curves. Also plotted are the measured S factors from this work, those from previously published data [4,10,12,19], and the proposed contribution from $1/2^{+}$ states predicted in Ref. [6].

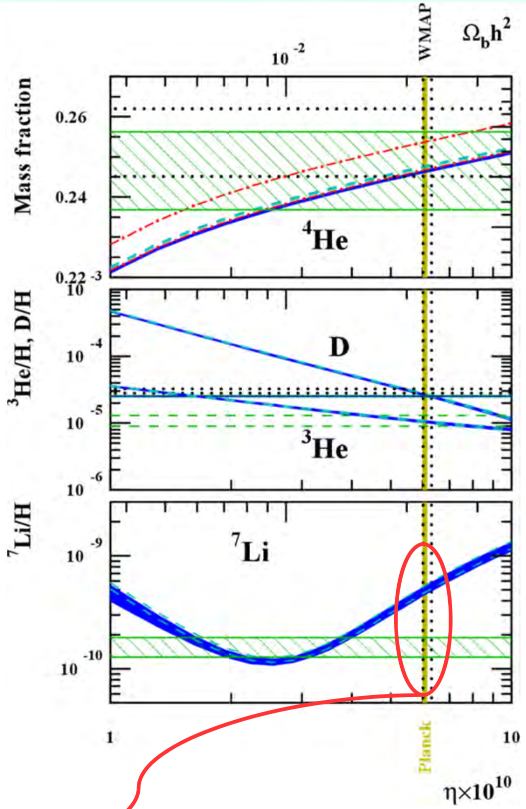
Direct data...C.E. Beer, et al.

THM data

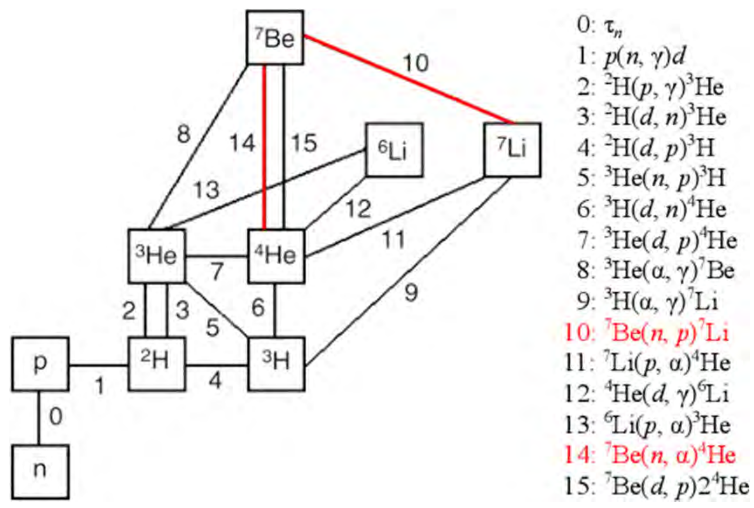
C.E. Beer, Phys. Rev. C 83, 042801(R) (2011)

Smeared to THM resolution

Cosmological ^{7}Li problem



A. Coc et al. J. Cos. Astropart. Phys. 2014

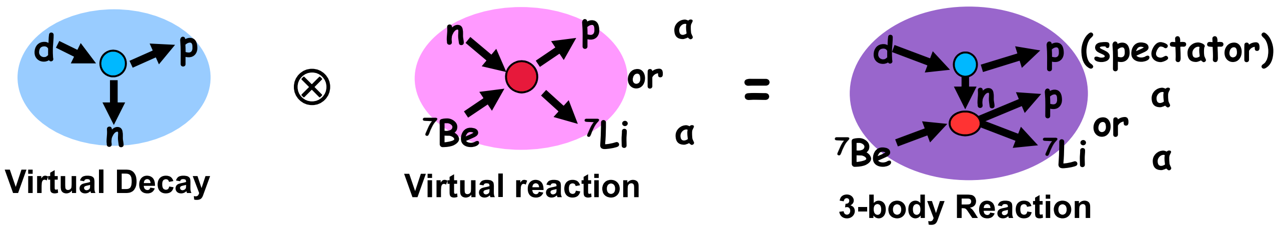


Iocco et al. Phys. Rep. 2009

- ^{7}Li problem... disagreement between theory and observation by a factor of 3−4
  - Due to CMB obs.? Low-metallicity stars obs.? Standard BBN model? Nuclear Physics?
  - ^{7}Be abundance in the end of BBN determines ^{7}Li predominantly
  - $p(n,\gamma)d$, ^{3}He$(d,p)^{4}$He, ^{7}Be$(n,p)^{7}$Li, ^{7}Be$(n,\alpha)^{4}$He, ^{7}Be$(d,p)2\alpha$, etc.

Trojan Horse Method for RI + neutron

- Trojan Horse method: (Spitaleri+ Phys. Atom. Nucl. 2011)
- $^{7}Be(n,p)^{7}Li$, $^{7}Be(n,\alpha)^{4}He$ via $^{2}H(^{7}Be,^{7}Lip)^{1}H$, $^{2}H(^{7}Be,\alpha\alpha)^{1}H$
- PWIA applicable when Quasi-free mechanism is dominant



$$(\text{Kinematic Factor})\cdot|\Phi(P_s)|^2 \times \frac{d\sigma^{HOES}}{d\Omega} \propto \frac{d^3\sigma}{d\Omega_p\, d\Omega_{7Li}\, dE_{cm}}$$

Calculated by Monte Carlo simulation

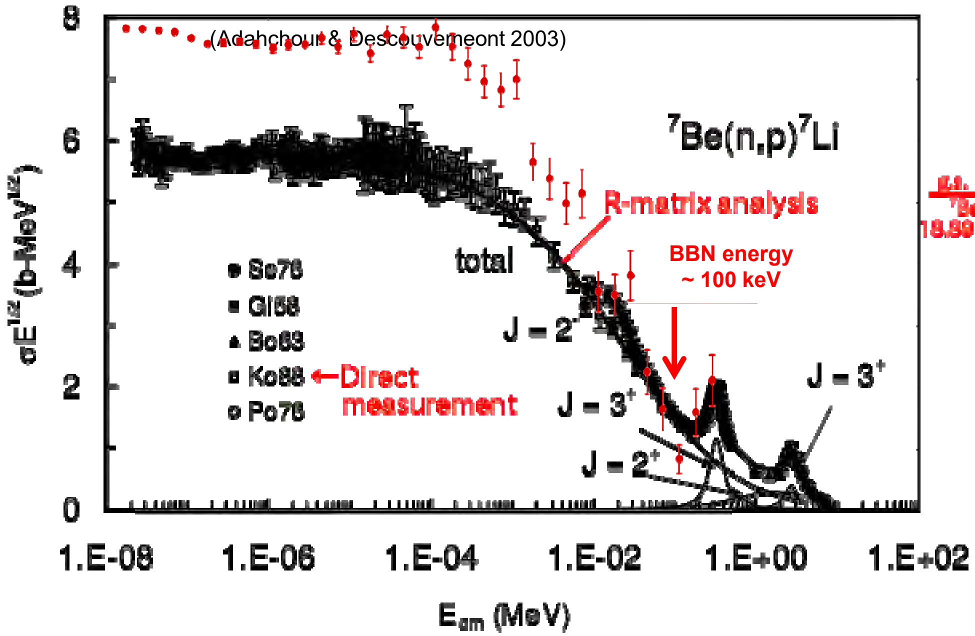
Half-off energy-shell 2-body cross section

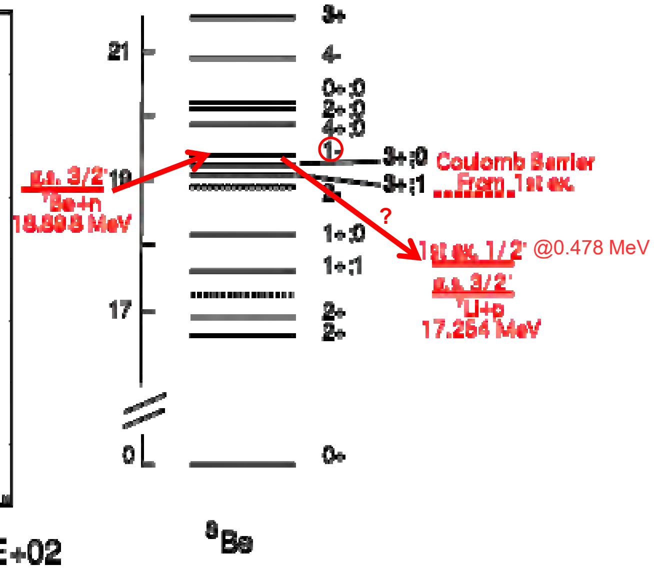
Measured at $E_{d\text{-}7Be}$ > Coulomb barrier

↑

σ^{OES} = Normalization × σ^{HOES} × Penetrability

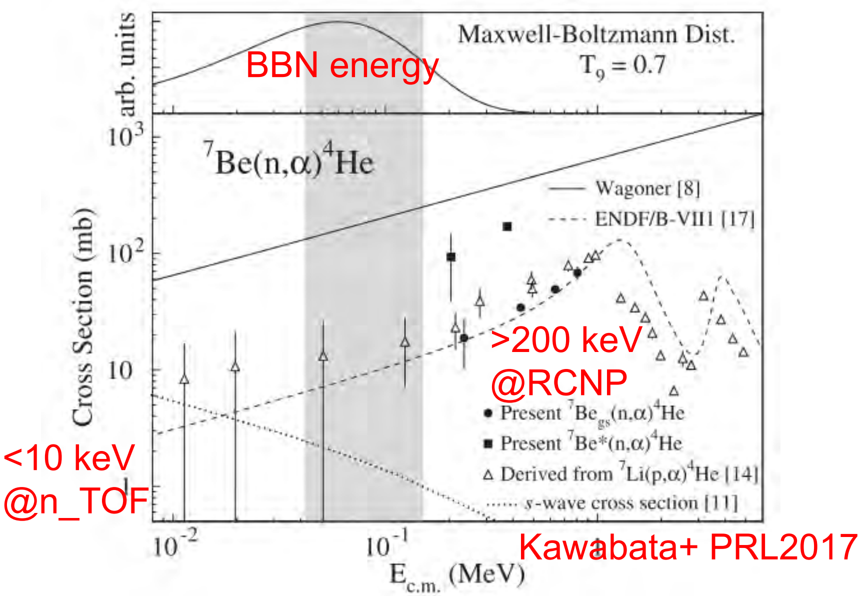
^{7}Be(n, p)^{7}Li (Q = 1.644 MeV)

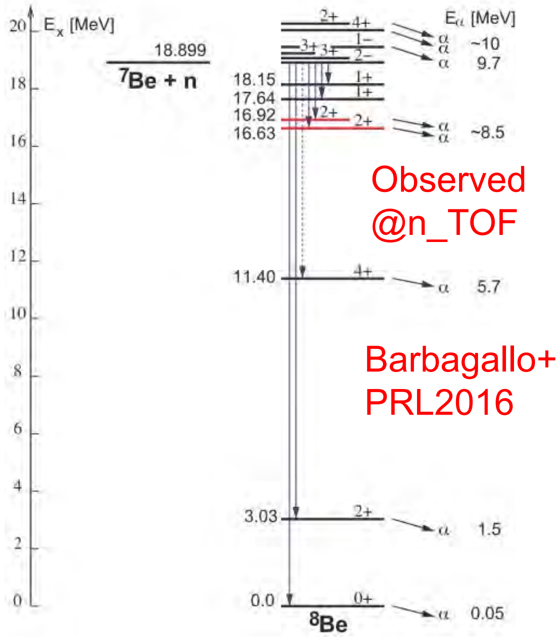




- Sensitivity: $\partial \log Y_{7Li} / \partial \log \langle \sigma v \rangle_{7Be}$ = −0.71 (Coc & Vangioni 2010, Cyburt+ 2016, etc.)
  If 5 × higher rate ➡ ^{7}Li problem solved
- Direct measurement up to 13.5 keV, time-reversal reactions at higher energies.
- R-matrix analysis: Adahchour & Descouvemont 2003.
- New n_TOF measurement: enhancement below BBN energies (Damone+ PRL 2018)

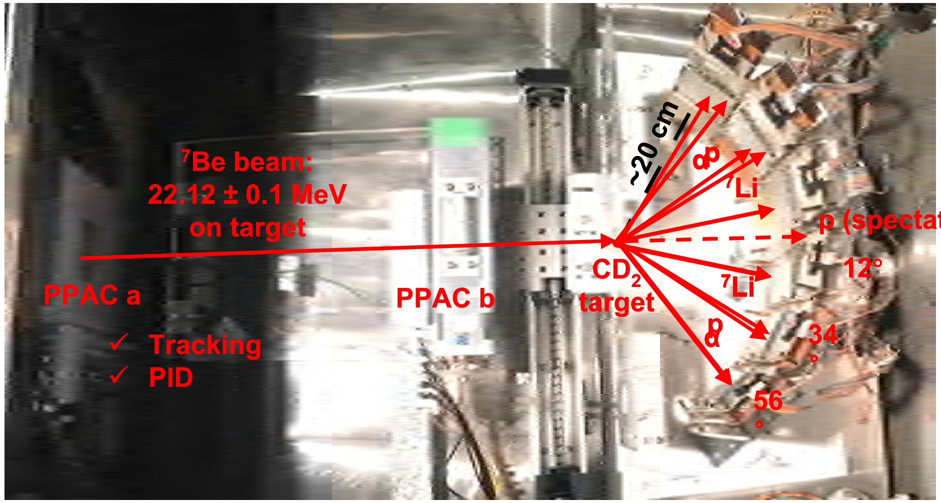
$^{7}Be(n, \alpha)^{4}He$ (Q = 18.990 MeV)





- Hou et al. PRC 2015: evaluation from $^{4}He(\alpha,p)^{7}Li$
- Barbagallo et al. PRL 2016: s-wave measurement @ nTOF
- Kawabata et al. PRL 2017: p-wave measurement @RCNP
- Lamia et al. APJ 2017: evaluation of $^{7}Li(p,\alpha)$ data measured by THM.
- Recent works consistent... Yet no direct data in the BBN range.

Experimental setup



- 6 ΔE-E position sensitive silicon telescopes
- ^{7}Li-p and α-α coincidence measurements

… spectator not measured

- CD_2: 64 μg/cm^2

➡ ΔE_{beam} ~ 150 keV

➡ To resolve $E_x(^7Li^{1st})$ = 478 keV

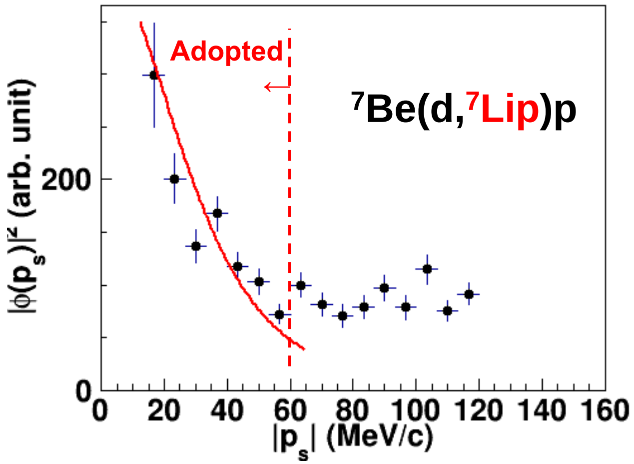
- Hamamatsu Charge-division PSD: position resolution ~ 0.5 mm

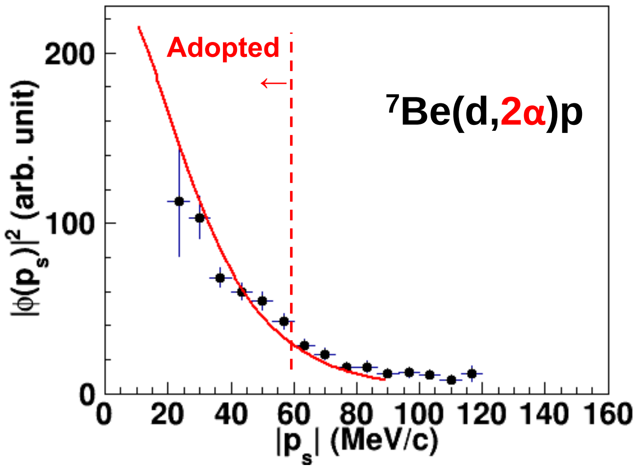
➡ Total angular resolution (PPACs & PSDs & alignment) ~ 0.5° ➡ ΔE_{cm} ~ 60 keV

Momentum distributions of the spectator p

$Y_{exp}/Y_{sim} \propto d^3\sigma/(d\Omega_p d\Omega_{7Li} dE_{cm})$ / KF $\propto |\Phi(p_s)|^2\, d\sigma/d\Omega$

~ $|\Phi(p_s)|^2$ at a fixed $E_{c.m.}$ and $\theta_{c.m.}$ (⇔ 2-body cross section is const.)

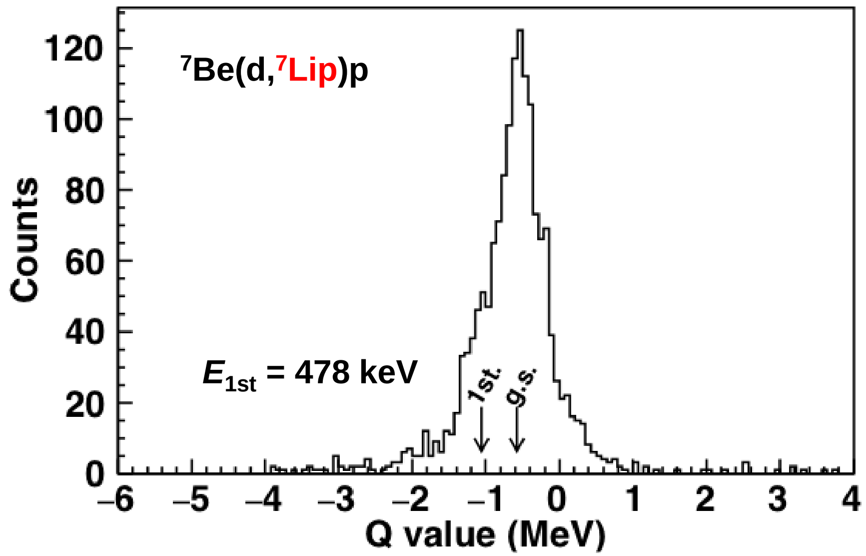


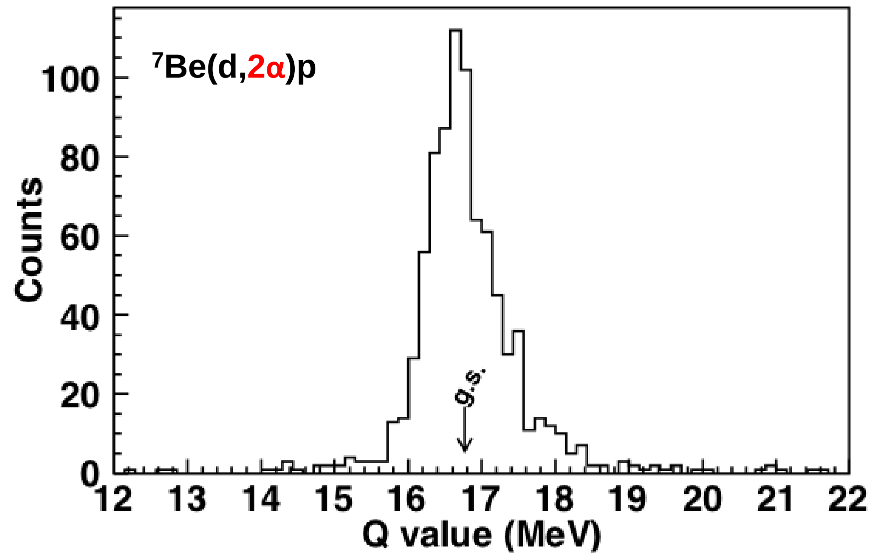


Hulthén function in momentum space for p-n intercluster motion (PWIA app.)

Good agreement up to 60 MeV/c
Evidence that quasi-free contribution is dominant.→ THM is valid!

Q-value spectra of the 3-body channels





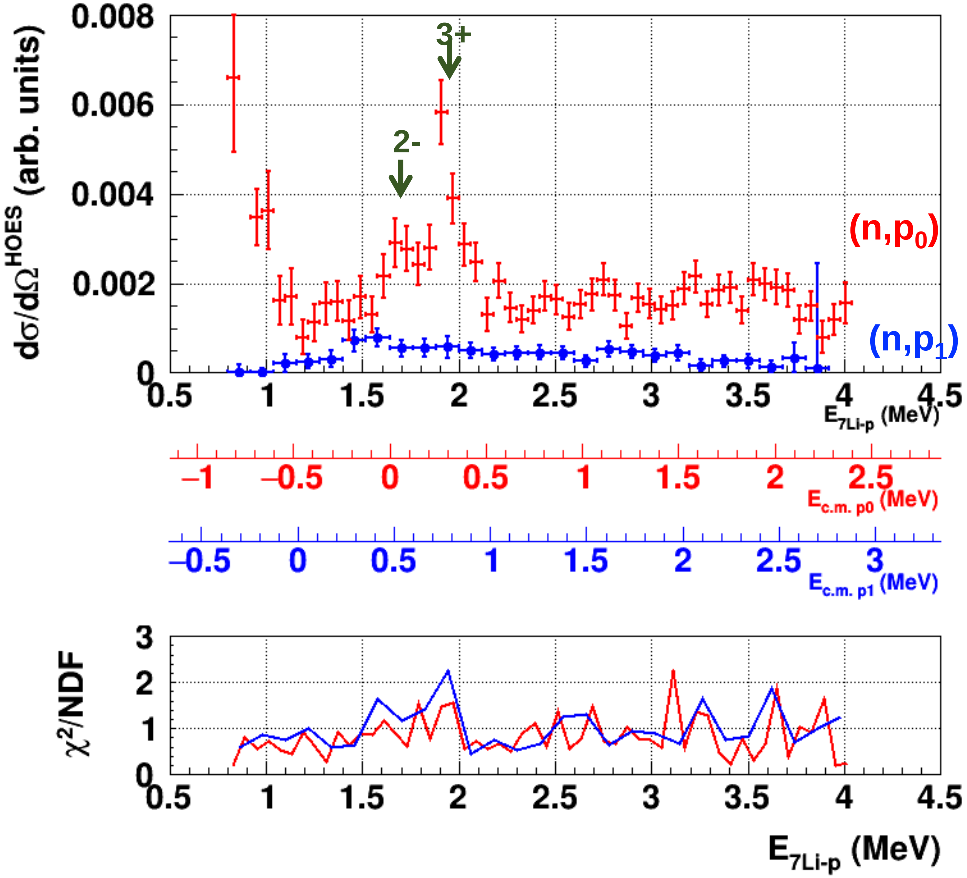
Reaction	*Q*-value (MeV)
$p+2\alpha$	16.766
$^{7}Li+2p$	-0.589
$^{7}Be+n+p$	-2.225
$^{5}He+p+^{3}He$	-4.547

$$Q_{3body} = E_1 + E_2 + E_3 - E_{beam}$$

$$\Delta Q_{3body} \sim \sqrt{(\Delta E_1^2 + \Delta E_2^2 + \Delta E_3^2 + \Delta E_{beam}^2)}$$

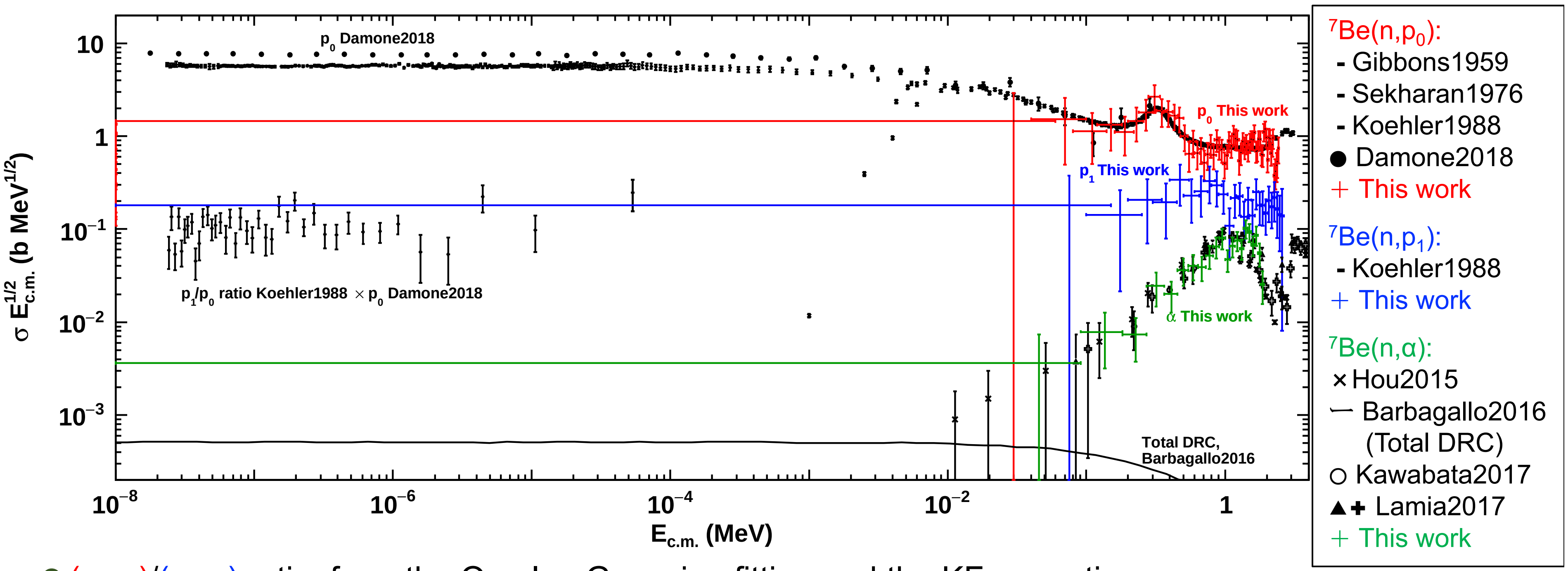
~ 200 keV expected with 64 μg/cm^2 CD_2

Gaussian fitting to Q-value spectra



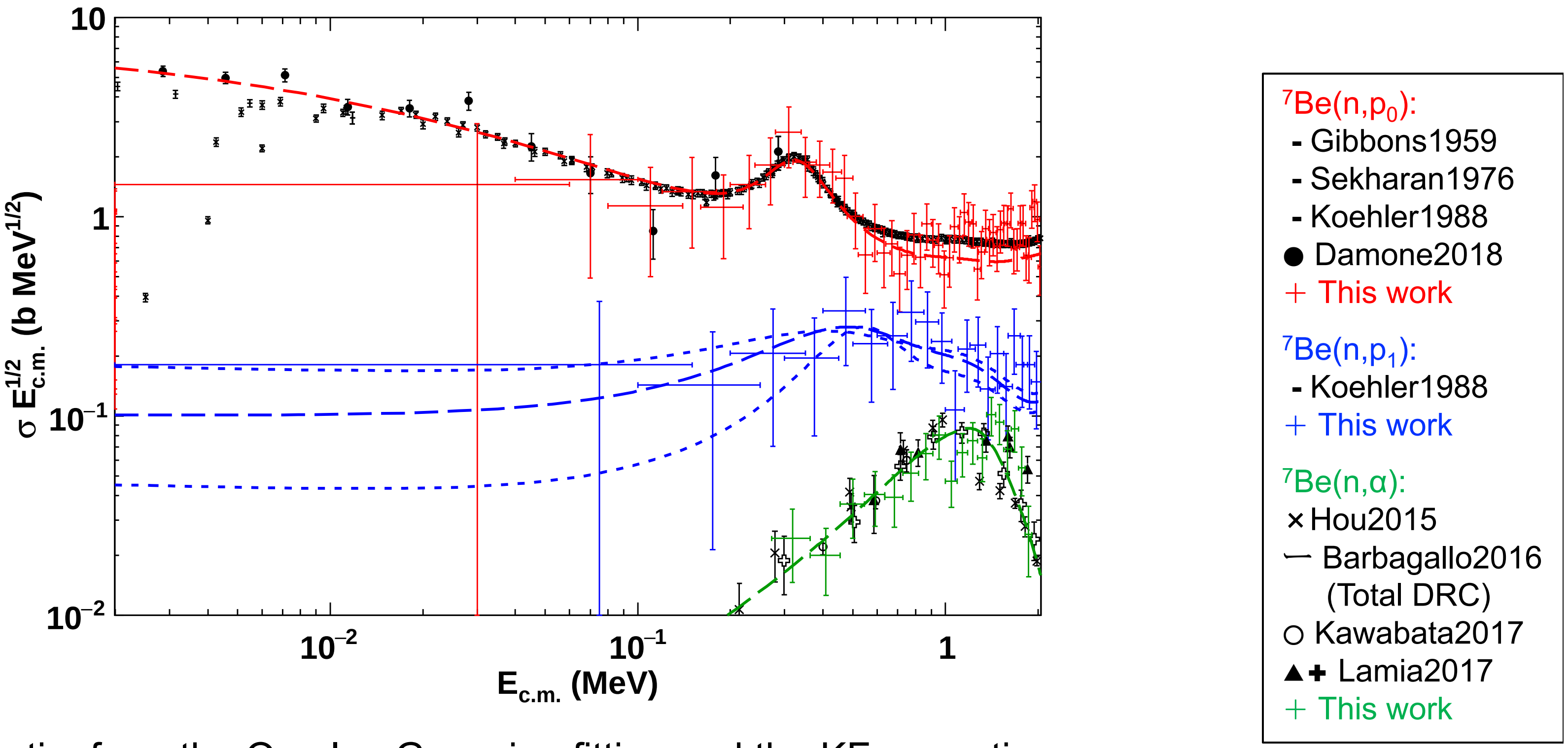
- Isotropy assumed (as no strong angular dependence seen)
- Checked systematic change of widths & peaks
  ➡ Reduces errors

Cross sections and R-matrix analysis



- $(n,p_0)/(n,p_1)$ ratio: from the Q-value Gaussian fitting and the KF correction
- (n,p_0), (n,p_1) penetrability (preliminary): assuming 1/v correction (s-wave)
- (n,α) penetrability (preliminary): assuming p-wave correction (consistent with Kawabata2017)
- (n,p_0), (n,α) normalization: to the previous data

Cross sections and R-matrix analysis



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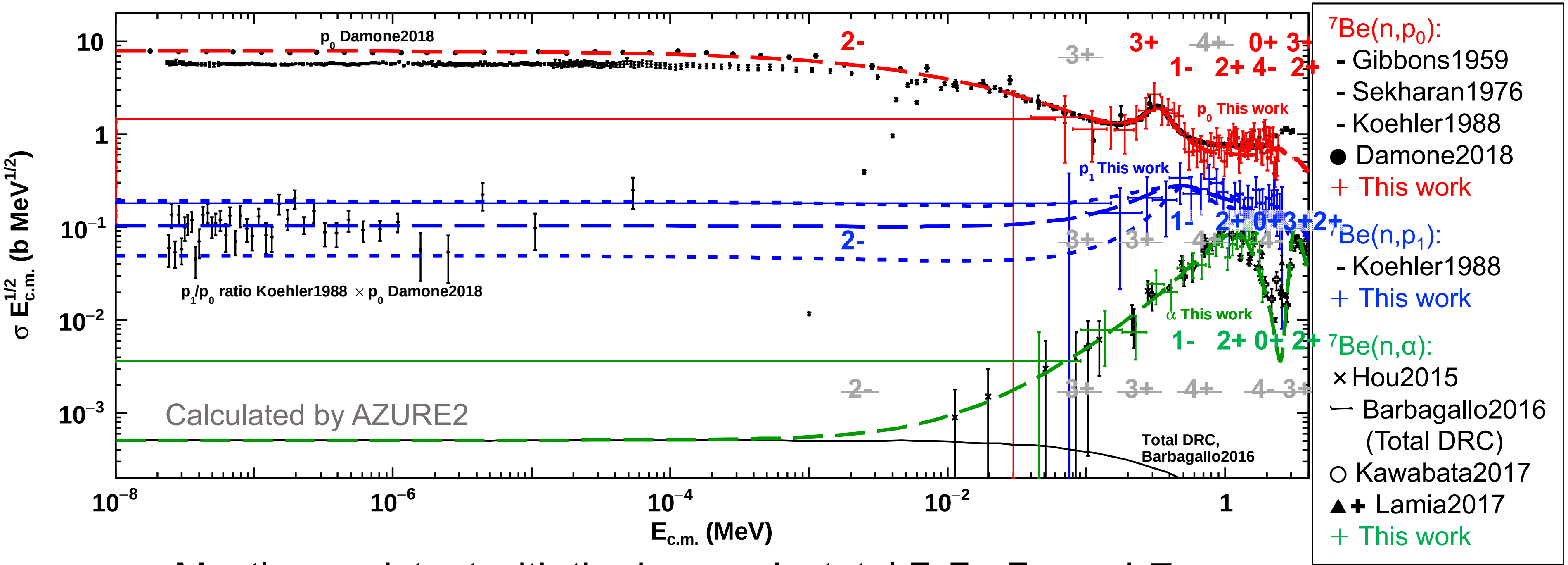
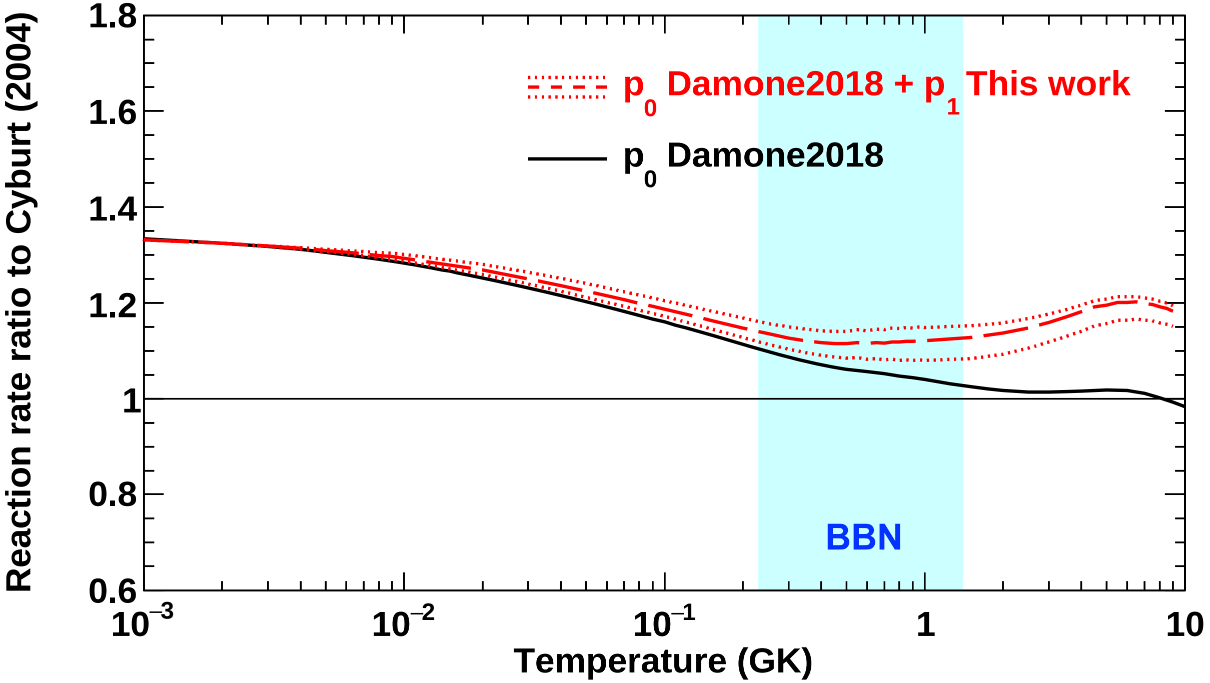
Cross sections and R-matrix analysis



- Mostly consistent with the known J^{π}, total Γ, Γ_n, Γ_{p0} and E_x
- No confliction with the Wigner limits. (except 2- Γ_n)
- $l \leqq 2$ only. (except higher-lying 3+)
- Included only n-emission channels.

^{7}Be(n,p) Reaction rate



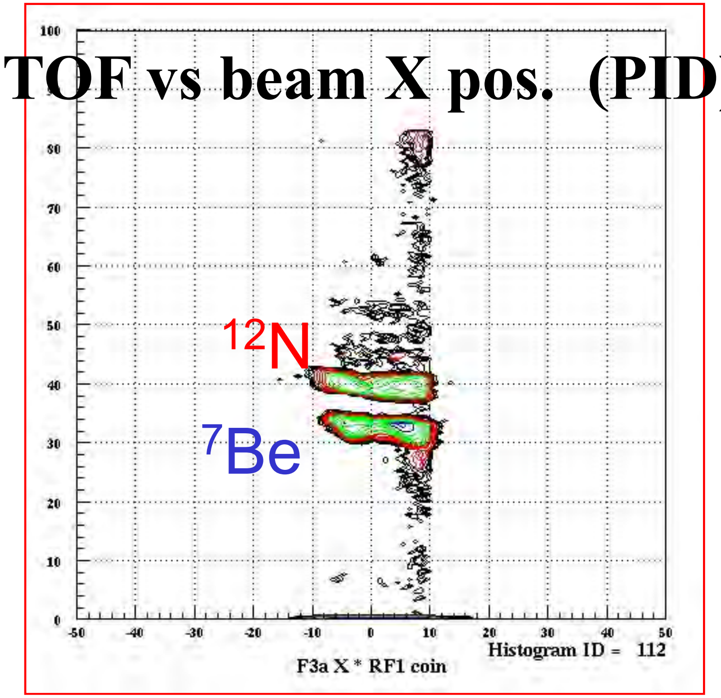
This work:
~ 15% higher rate (preliminary)
➡ ~ 90% ^{7}Li abundance (preliminary)
(with a sensitivity
$\partial \log Y_{7Li} / \partial \log \langle \sigma v \rangle_{7Be} = -0.71$)

n_TOF results:
~ 5% higher rate in BBN range
➡ 96% ^{7}Li abundance

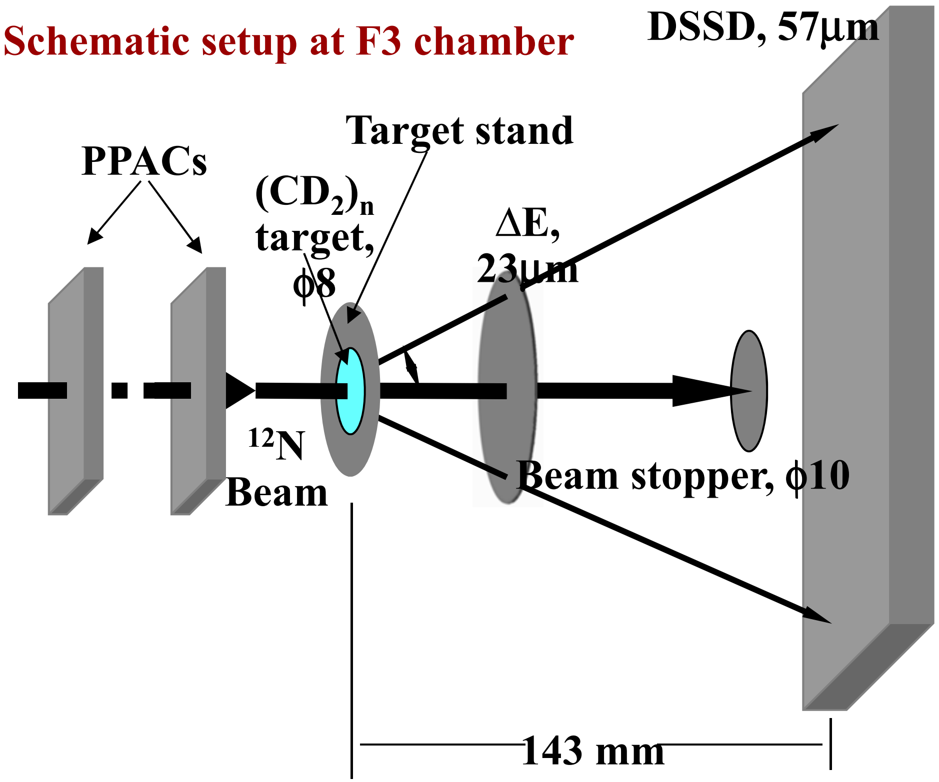
ANC measurement; $^{12}N(p,\gamma)$ by $^{12}N(d,n)$

- Hot burning process (rap) in massive stars.
- ^{12}N: produced by $^{10}B(^{3}He,n)$, 1k-2k pps on the CD_2 target.
- ^{12}N beam purity: ~50% on the ΔE detector. (Main contaminant: ^{7}Be)

TOF vs beam X pos. (PID)



Schematic setup at F3 chamber

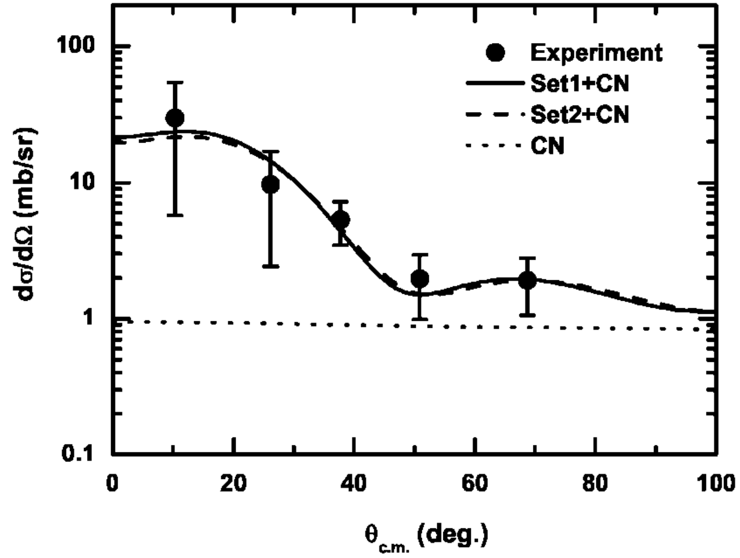


^{12}N(p,γ) by ANC

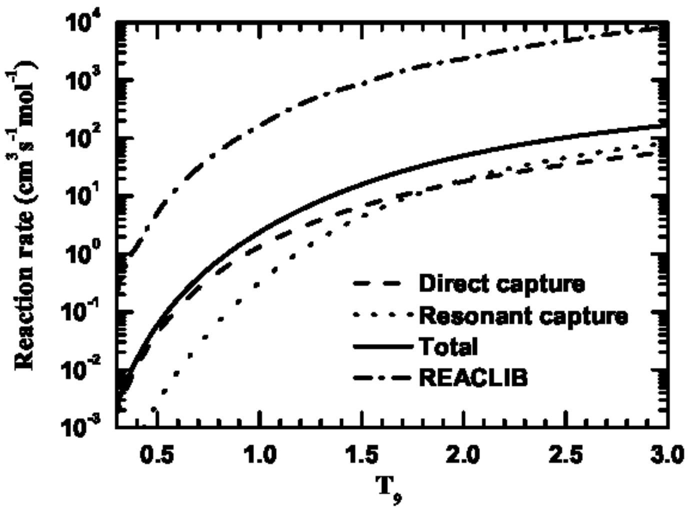
- ^{12}N(d,n)^{13}O⇔ ^{12}N(p,γ)^{13}O

- Differential cross section

→ANC by optical potential fitting



→^{12}N(p,γ) reaction rate evaluated, 2 orders of magnitude smaller than REACLIB.



B. Guo et al., Phys. Rev. C (2013)

Summary

- CRIB is a low-energy RI beam facility in RIBF operated by CNS, University of Tokyo, providing low-energy (<10MeV/u) RI beams of good intensity and purity.

- Interests on indirect determination of astrophysical reactions, using RI beams:
  - Alpha resonant scattering to study resonance properties
  - Indirect method measurements (THM and ANC)
  - Al-26 isomeric beam for the cosmic gamma-rays

- Visit CRIB webpage for more information. http://www.cns.s.u-tokyo.ac.jp/crib/crib-new/